A blockchain- and IoT-based smart product-service system for the sustainability of prefabricated housing construction

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Abstract: Prefabricated housing construction (PHC) will be widely recognized as a contributor to consumption reduction and sustainability enhancement if inherent drawbacks (e.g., fragmented management, poor connectivity) can be addressed efficiently. The promotion of advanced information and communication technologies (ICT) has triggered the evolvement of smart product-service systems (SPSS), where a smart connected product (SCP) acts as a critical role in the interconnection of physical components and specialized services for value co-creation. Hence, it is promising to realize the positive improvement of PHC based on an SPSS approach, especially during the challenging post-COVID-19 pandemic era. We developed an intelligent platform based on service-oriented manners with practical case demonstration for interactive innovation of PHC shareholders, among which prefabricated components (PC) have been defined as the SCP in PHC, and a platform-enabled approach has also been adopted in the way of SPSS. Furthermore, distributed security technology viz. blockchain along with inclusive ICT (e.g., Internet-of-Things (IoT), Cyber-Physical System (CPS), and Building Information Modeling (BIM)) are employed jointly to spark new modes of smart construction. Meanwhile, valuable exploration and open research directions are expected to facilitate the PHC supply chain to become more resilient in sustainability.

Keywords: Prefabricated Housing Construction; Smart Product-Service Systems; Blockchain; Internet of Things; Sustainability

Nomenclature

BIM Building Information Modeling

BT Blockchain Technology

CPS Cyber-Physical System

DLT Distributed Ledger Technology

ICT Information and Communication Technologies

IoT Internet of Things

PC Prefabricated Components

P2P Peer-to-Peer

PHC Prefabricated Housing Construction

PSS Product-Service Systems

RFID Radio Frequency IDentification

SCM Supply Chain Management

SCP Smart Connected Product

SCR Supply Chain Resilience

SPSS Smart Product-Service Systems

1. Introduction

Sustainability, as one of the core issues drawing global attention, has played a crucial role in the construction industry through the ages (Du et al., 2019). Previous research indicated that the construction industry's carbon emissions and worldwide energy usage have incrementally increased, accounting for 30% (Pan and Garmston, 2012) and 40% (John et al., 2016), respectively. Meanwhile, without effective strategies, the volume of its consumption will keep rising by approximately 50% by 2050 (IEA, 2013). In this perspective, the transformation of the construction industry is particularly critical for environmental conservation and sustainable development. Prefabricated housing construction (PHC), with its widely recognized contributions, such as decrease of schedule delay (Gao and Tian, 2020), saving of labor usage (Li et al., 2018), reduction of construction waste and carbon emission (Zhou et al., 2019b), has become a trend in lean construction. However, if PHC cannot overcome its intrinsic drawbacks (e.g., low productivity, poor interoperability, inefficient management, etc.), it can hardly become an eligible contributor to sustainability (Du et al., 2019).

PHC relies on the stable operations of supply chains (Teng and Pan, 2019), which mainly includes building design, prefabricated components (PC) production, logistics, and prefabrication assembly. Moreover, sustainable supply chains are committed to providing shareholders with satisfactory products as well as valuable services in an economized and environmental-friendly manner to meet particular needs (Li et al., 2018). Goedkoop (1999) firstly defined such a proposition as product-service systems (PSS); thereafter, PSS has been extensively regarded as an economic and energy-saving method to realize sustainability (Liu et al., 2018). Recently, emerging information and communication technologies (ICT), for instance, Cyber-Physical Systems (CPS), Building Information Modeling (BIM), Internet-of-Things (IoT), and blockchain, have triggered a promising evolution of PSS, which is known as smart PSS (SPSS) (Valencia et al., 2015). Moreover, the smart connected products (SCP) and its delivered e-services served as the essential constitution of SPSS (Zheng et al., 2018). By transforming from product-centered to service-centered, SPSS will give rise to the next generation of ICT-driven productivity growth (Porter et al., 2014). Besides, once products and services are recognized as a bundle, digital services are more capable of satisfying the requirements of shareholders compared to exclusively employing physical products (Zheng et al., 2019a).

Specifically, as for PHC, it has several construction sites, long construction cycles, large industrial chains, and various uncertain situations (Araújo et al., 2020), inevitably generating mass data which can be categorized into two types: shareholder-generated and product-generated (Zheng et al., 2018). Shareholder-generated data are mainly stemmed from mutual communication among designers, producers, transporters, and assemblers, while product-generated data can be regarded as its status information captured by machines from particular stages. However, owing to the lack of practical approach to fully utilize plentiful data, even worse, fragmentation of information frequently can hinder collaboration in the supply chain. As a result, the conventional PHC faces several challenges in weak interaction and smart decision-making (Tao et al., 2019). Besides, the PHC supply chain is a network of cross-echelon organizations that are connected by information, material, services, product flows, and capital flows among stakeholders (Gao and Tian, 2020); thus, making reliable products and value-added digital services as a bundle is paramount (Zheng et al., 2019b).

As a result, it is feasible to realize the promotion of PHC based on SPSS. PCs can be regarded as SCP. Integrated ICT enables various shareholders to acquire SCP status data on a real-time basis while connecting diverse stages, responding promptly to disturbing incidents, and realizing the reduction of energy consumption. Nevertheless, the application of SPSS has been embraced in manufacturing industries (e.g., smart devices, machine tools, etc.). Scarcely related works demonstrate the connection between SPSS and the construction industry (PHC particularly), and very few works of literature concentrate on how services and products can be integrated as a bundle to fulfill users' specialized needs. Furthermore, the platform-based approach was considered as a fundamental method to leverage the value of SPSS (Thomas et al., 2014), and diverse PHC stages should be centralized to make the supply chain more resilient, which also shows inadequate support in the literature.

To address the given limitations, this article develops an intelligent platform based on inclusive technologies, incorporating CPS, IoT, BIM, and blockchain for SPSS innovation in PHC. The research objectives are: (1) to develop a smart platform to gather, process, communicate, and leverage information through the lifecycle of PHC; (2) to employ blockchain- and IoT-based, BIM- and CPS-enabled platform to facilitate the real-time management of PHC supply chain; (3) to demonstrate the effectiveness and performance of the proposed platform based on SPSS approach with the practical application.

The remainder of the paper is organized as follows: Section 2 presents a holistic review of related works. In Section 3, we illustrate the architecture of the platform. Then, we introduce the function development of the platform in Section 4, followed by a real-life case study that employs the proposed platform based on SPSS in Sections 5. The conclusions and directions for future research are summarized in Sections 6.

2. Related works

2.1 Prefabricated housing construction

PHC, with its generally recognized benefits of standardized production, associated services, and energy-saving construction, has been regarded as an eligible contributor to handling various building challenges (Teng et al., 2018). Compared to cast-in-situ techniques characterized by dense scaffolds, dusty installation, wet working, formwork systems, and massive demolition waste, PHC aims to transfer as many on-site construction components as possible to manufacturing factories under standard regulations and controllable production patterns (Li et al., 2020). As a result, the advantages include, but are not limited to, construction cost and time savings, enhanced quality, safe and manageable working environment, and decreased construction waste and energy consumption (Li et al., 2017). PHC appears to be significant to integrated manufacturing, which not only requires large investments and long construction periods but also has a large group of suppliers and subcontractors (Li et al., 2020). Governments have taken a positive attitude toward formulating strategies and policies to support the implementation of prefabricated buildings. In reality, some countries and regions, such as Singapore, Australia, and Hong Kong, benefited from PHC as it addresses the limited on-site construction environment, labor shortage, and resource scarcity (Arashpour et al., 2016).

Thus, the adoption of PHC is promising. Therefore, it is indispensable to pay more attention to handling complex supply chain management (SCM) in PHC. The concept of SCM was introduced in the construction industry from the manufacturing industry in the 1980s (Segerstedt et al., 2010). The scope of supply chain collaboration has been divided into horizontal and vertical partnerships (Barratt and Oliveira, 2001). As the scale of PHC continues to expand, information integration and technology sharing become key processes in SCM. The application of SCM is hindered by several factors. For instance, the on-site and off-site working sites of PHC are separate, and suppliers are often not involved in PCs' design (Turken and Geda, 2020), leading to delivery delays, schedule extensions, disorderly on-site processes, and vague client demands (Arashpour et al., 2016). Researchers described the complexity of PHCSCM in the following ways: (1) a longer chain caused by two or more production environments, including factory and site; (2) additional predesign works due to the completion of PCs ahead of time; (3) more extended error correction periods; and (4) higher requirements for dimensional accuracy (Koskela, 2003). Nevertheless, the actual deployment and implementation of PHC are still facing challenges. Since they lack an effective way for nodes to participate in a dynamic supply chain collaboration, the benefits of PHC remain rhetorical (Du et al., 2019).

2.2 Blockchain for IoT and CPS

The CPS initially resulted from the intersection between physical devices and intangible Internet (Alippi and Ozawa, 2019), which enables tangible devices to realize precious communication, remote coordination, and intelligent, sophisticated control. CPS and IoT share the same goal, which aims at seamlessly integrating cyber and physical worlds (Tao et al., 2019). CPS offers a comprehensive and interactive structure that consists of various ICT to satisfy its original requirements; simultaneously, IoT and BIM can be integrated into detailed application of CPS. Additionally, in PHC, construction data can be captured by monitoring instruments instantly and uploaded to the cyber sections for subsequent analysis and utilization (Zhou et al., 2019b); thus, real-time management and intelligent information interaction can be achieved. However, with CPS was interconnected in networks, data storage inevitably faced unpredictable security vulnerabilities and privacy risks (Li et al., 2020). To address these defects, the consensus-driven and decentralized blockchain technology and the combination of cryptographic processes behind it could provide a useful alternative (Tao et al., 2018).

Blockchain is an innovative computer technology application model with distributed storage, point-to-point (P2P) transmission, consensus mechanism, and encryption algorithm (Lee, 2019). On the one hand, blockchain can play an important role in secure decentralization; the ledger is distributed across every single node in the blockchain who are the participants, thus allowing for verification without the necessity of third-parties. Therefore, in SPSS, the data structure in a blockchain is append-only, and it is impossible to alter or delete data without every node permission (Peck and Moore, 2017). On the other hand, since the transactions are preciously recorded in chronological order, consequently, every block is time-stamped, and it can be tracked along the chain to its point of origin (Liu et al., 2020). Meanwhile, all businesses can pre-set conditions on the blockchain, which facilitate customers easily involved in the SPSS chains (Feng et al., 2020). The most common blockchain types include public, private, and consortium blockchains (Feng et al., 2020). Apart from its wide adoption in intellectual finance, digital insurance, and smart logistics (Liu et al., 2020), there are three categories in construction practices (Peck and Moore, 2017), namely, (1) notarization-related applications to reduce the time for authenticating documents; (2) transaction-related applications to facilitate automated procurement and payment; and (3) provenance-related applications to improve the transparency and traceability of construction supply chains. It is believed that blockchain constructs an internal link with IoT and CPS regarding various functions, e.g., for monitoring assets, sensing certain features, and actuating particular actions (Lee, 2019). As shown in Fig. 1, for instance, several nodes (PHC shareholders) are pre-established for recording; after passing the on-chain verification step, unprecedented security benefits are brought due to its distributed storage, encrypted transmission, and reliable security. The exploitation of blockchain in the realm of IoT and CPS—and future ICT infrastructure in general—has the potential to enable various capabilities and use cases in those systems (Feng et al., 2020).

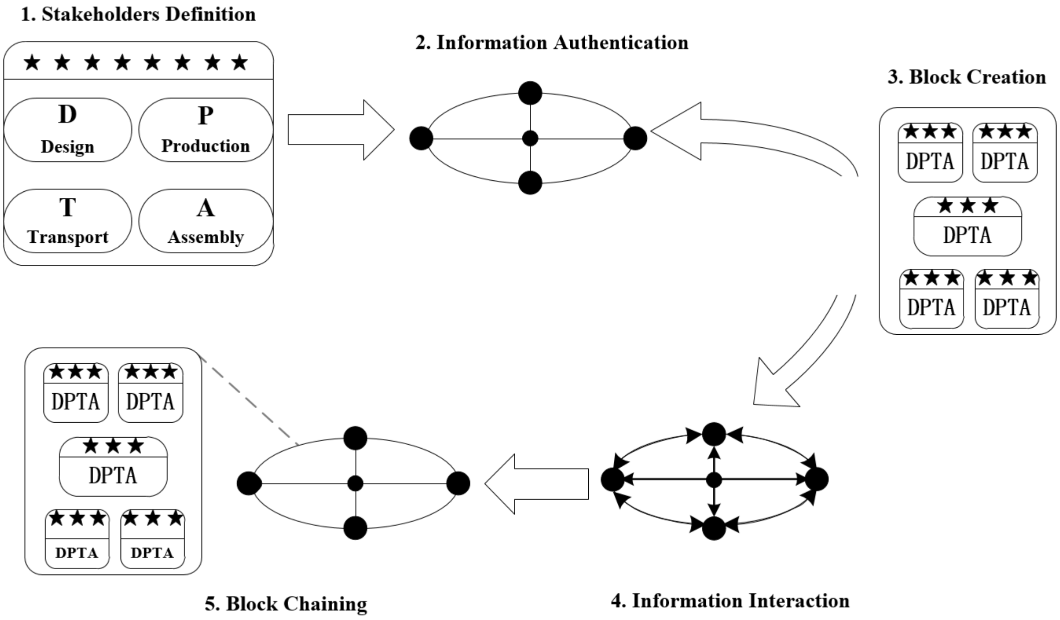

Fig. 1. The procedure of blockchain-based information and service exchange

2.3 A smart product-service system for sustainability

PSS, referring to the combination of valuable services, physical products, and associations of participants, has been deemed an efficacious method to enhance customer satisfaction and mitigate environmental impacts (Goedkoop, 1999). With the advancement of intelligent technology, SCPs played a fundamental role in digitalization services, which aim at making the PSS smarter, i.e., an SPSS (Valencia et al., 2015). The SPSS exceedingly counts on the connectivity and digitalization of the SCP (Liu et al., 2018); however, given that ICTs are embedded within the SCP itself rather than as simple additions to the previous PSS, it is a conjoined bundle to satisfy individual shareholders' requests for co-creation of value (Zheng et al., 2019a). Zheng and Wang (2019b) classified an SPSS into three levels: 1) the product-service level, where the SCP is employed as a sole scheme for customer requirements; 2) the system-level, where shareholders are integrated into the platform-based systems to realize optimal value co-creation via seamless collaboration and prompt interaction; and 3) the system-of-systems level, from the perspective of an ecosystem, which overcomes the limits of an individual SPSS and further connects interrelated systems to achieve more significant impacts. No matter which level, it is generally recognized that an SPSS is beneficial for sustainability (Reim et al., 2015). For enterprises, ICT facilitates them to gather data and effectively optimize their response strategies, thereby reducing energy consumption (Zheng et al., 2019a). For clients, they are no longer passively involved in the process of value generation; reversely, shareholders are contributing to the active co-creation of value for personalized servitization (Valencia et al., 2015). Hence, the SPSS and its extensive applications have been embraced in smart manufacturing, for instance, shaft manufacturing (Tao et al., 2018), smart water dispensers (Zheng et al., 2019a), or wearable masks (Zheng et al., 2018). Nevertheless, the construction industry, which ranks the top in energy consumption, rarely developed a holistic design for SPSS innovation in detail; where the PC can serve as SCP in PHC, real-time data can be collected by CPS, where every shareholder can be coordinated via platform-based systems and escalate to a smarter, greener, more energy-efficient construction style. As depicted in Fig. 2, the design, production, transportation, and assembly of PHC used to be islands of information that are now integrated through a platform based on SPSS.

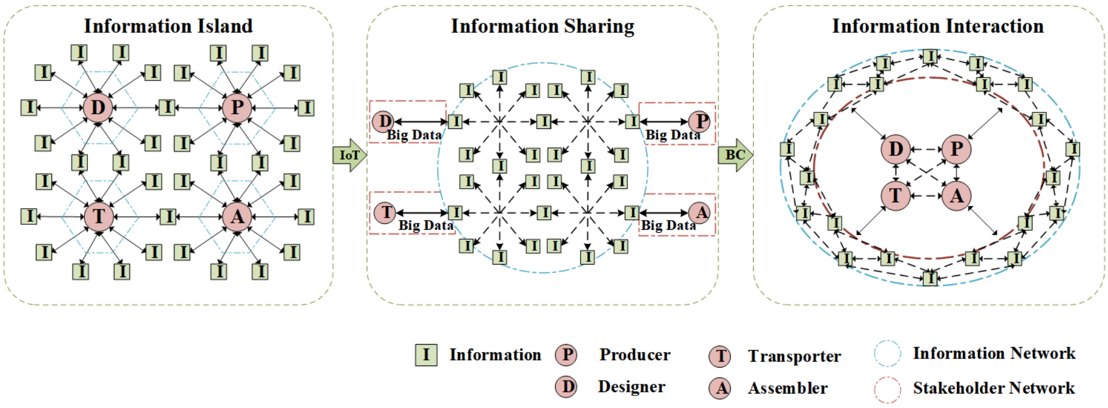

Fig. 2. Evolution of SCM through the platform based on SPSS

3. Architecture of the intelligent platform

A platform-based system was proposed, and BIM, CPS, IoT, and blockchain were incorporated jointly to foster mutual collaboration and data exchange services sustainably to fill the mentioned gaps. Detailed operation and security structures are illustrated in this section.

3.1 Platform operating structure

As illustrated, a platform-based model is indispensable to reach the SPSS implementation (Cenamor et al., 2017), yet conventional PHC management systems have always employed temporary project departments for project construction management; thus, the management of each PHC phase can be readily separated, coordinated management will be more laborious to realize, information islands will be generated inevitably, and the project's progress, quality, risk, and fund-tracking will be arduous to control. Therefore, considering the characteristics of PHC, PCs are highly adopted as SCP in the product-synergic platform that leverage edge technologies to present modular interactions and overcome these crucial defects.

The operation structure of the platform is depicted in Fig. 3 for SPSS innovation, which can be divided into four levels, namely, the sensing layer (SCPs-gathering), intelligence layer (data-interacting), big data processing layer (cloud-computing), and application layer (value-delivering). Hence, collaboration is facilitated by removing barriers among the various PHC parities.

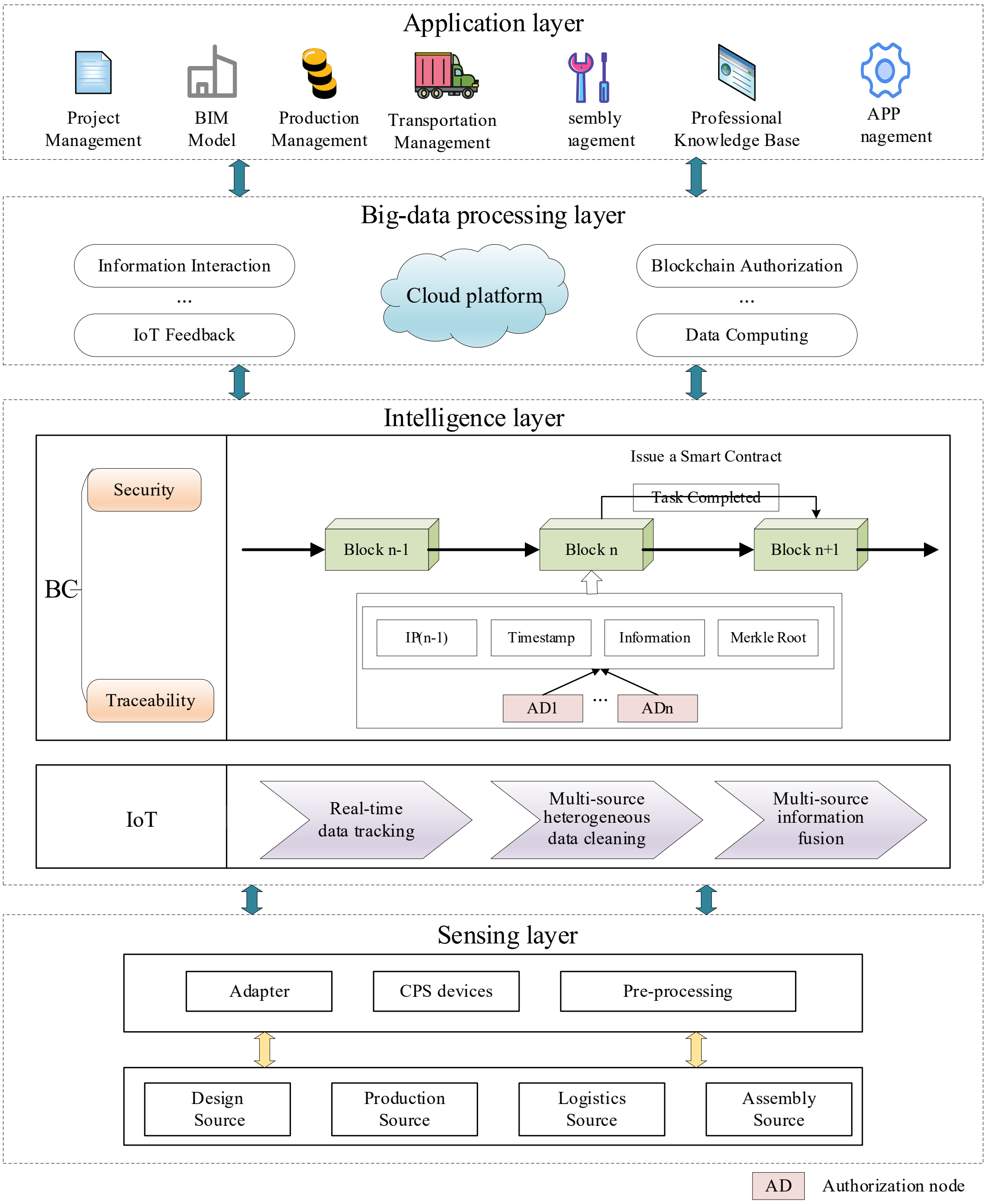

Fig. 3. Operation structure of the platform for SPSS services innovation

3.1.1 Sensing layer

A sensing layer is responsible for accurately identifying and gathering adequate data from diverse providers, which is a key section of the ultimate service innovation. In PHC, the prime data collected by SCPs originate from stakeholders (information upload), PC (status monitor), and materials (consumption reading). In the process of system management and control, this layer will conduct comprehensive data collection and management on project safety, quality, schedule, and other aspects.

3.1.2 Intelligence layer

The intelligence layer that embodies the core value of the platform is mainly supported by IoT and blockchain technologies and serves as the bridge between the interface and data access layers. Hence, each system requires a reliable infrastructure to operate. Blockchain is capable of supporting the coordinated operation of information collection, transmission, and communication, and it provides a reliable basis for synergy. This layer implements the business logic and concentrates on the formulation of business rules or organizations; meanwhile, it provides support for the subsequent implementation of the system structure, where the database that is developed between elements allows autonomous interchanging and efficient exertion.

3.1.3 Big data processing layer

The big data processing layer involves computing diversified data from various providers, including primary documents, BIM, and schedules. The massive data stored in the database are submitted to the business layer. In contrast, the data processed by the business layer are interconnected and load back to the blockchain-encrypted database. Users' requirements are reflected in the application layer, which can simultaneously forward to the intelligent layer and realize an interactive response eventually. The data layer carries out data operations and then returns these data one by one to the specific users, thus achieving centralized and orderly management of data in the distributed system. This layer assesses and refines real-time data to maintain efficient connectivity; additionally, by refreshing the data and revising the analysis as needed, the collaboration of stakeholders meets the promotion.

3.1.4 Application layer

The application layer involves the application of relevant data for business management by diverse stakeholders. In the user interaction interface, this layer receives the data input by the user and then displays the data after sophisticated processing. According to the level and identity of users, the system then offers different access interfaces and assigns corresponding functions or data permissions. The shareholders, including the owner (e.g., government), design, production, transportation, and construction units, are integrated into the application layer. In addition, the application layer is also mainly responsible for the appropriate, accurate, and comprehensive management of the engineering process, receiving timely engineering instructions from the upper layer and offering timely feedback to ensure the convenient application of services for the system users. The integrated structure of the platform can realize rapid information feedback, which greatly enhances the resilience of the PHC supply chain.

3.2 Platform security structure

As cash flow and data exchange are generally performed to the accompaniment of project progress, it is commonly recognized that inconsistent provision terms, unauthentic supervision, and unveracious data will lead to inevitable disputes and lawsuits on information confidence and trustworthy resources (Yang et al., 2020), especially in the PHC whose procedures are decentralized. The off-site and discontinuous characteristics of the PHC supply chains match the distribution of blockchains well (Shojaei, 2019). Therefore, blockchain is employed to develop a more open, trackable, and transparent method to validate and guarantee the reliability of data throughout the supply chain.

3.2.1 Data security

The blockchain is a mode of Distributed Ledger Technology (DLT), where all the business processes are verified and digitized. It is a distributed network where no trusted authority is needed to maintain the verification of relevant parties. Instead, the cryptographic block can be chained once its authority is confirmed, and every transaction is visible to the connected blocks, meaning shareholders of the PHC are accessible to track construction history and check the recorded data conveniently. In PHC, there are four main data sources, namely, design stage, production stage, logistics stage, and assembly stage. The prime data collected by SCPs are from stakeholders (information upload), PC (status monitor), and materials (consumption reading) during these four stages, and then the relevant data will be encrypted and uploaded. As opposed to centralized architectures, various monitoring and decision schemes based on blockchains should be more scalable than conventional ones. Specifically, as shown in Fig. 4, the stakeholders in each stage of PHC upload encrypted data after completing data collection and processing, and secure data transmissions are conducted in the blockchains.

Without the consent of all the relevant personnel, all parties are incapable of modifying data but can view and utilize data within their respective authorities, thereby enhancing the credibility of generated data in PHC.

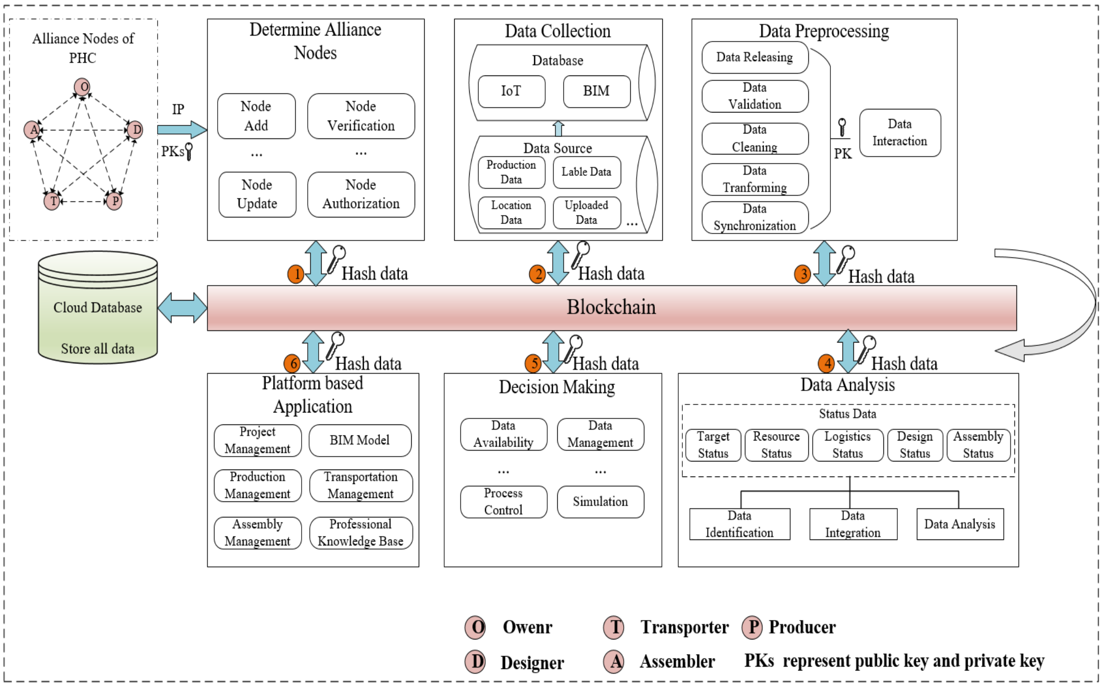

Fig. 4. Encryption mechanism of the platform with blockchain adoption

3.2.2 Application security

Blockchain is hack-resistant, tamper-proof, and immutable due to its distributed ledger and network verification process (Min, 2019). It is believed that projects can benefit from a more decentralized and agile approach where transparency is high, and various parties can be compensated for outcomes, as well as for work performed. The detailed value of application security is revealed below.

1) Smart contracts. For dealing with poor payment and execution issues in PHC, a blockchain-based and self-executed contract is adopted in the platform, where clauses and

rules are embedded originally, and cryptographic matters are settled to alleviate the defects caused by delayed payments and fallacious performance.

2) Information storage. Sustainability, as a critical goal of the proposed platform, cannot be realized if information sharing is absent. The blockchain enables massive construction data to be stored reasonably; in other words, a wide range of information can be utilized in a traceable, secure, and sustainable way due to its highly reliable database.

3)Supply chain management. Traceability and trackability act as fundamental roles in SCM. In the blockchain of the platform, suppliers and clients can verify mutual immutable qualifications and track previous records through the supply chain for value co-creation (see Fig. 5). Meanwhile, specific products/services can be monitored in real-time, which facilitate the smart management of the PHC.

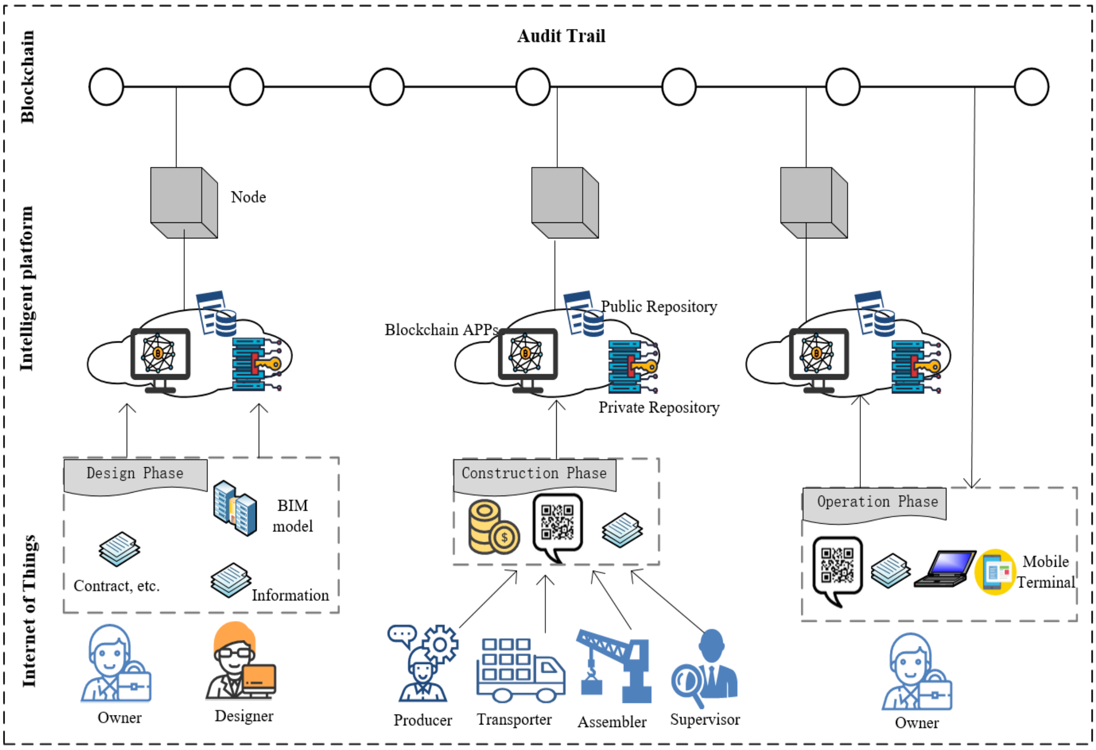

Fig. 5. Blockchain-based pattern for value co-creation

4. Function development of the intelligent platform

4.1 The overview of the platform function

The platform function development serves as the fundamental level of SPSS value co-creation. Fig. 6 depicts the overview of the workflow of each stage in this intelligent platform, where the detailed functions are preciously corresponding to specific needs. Especially, the critical function of the platform can be observed in three aspects: 1) Effective information interaction, 2) Real-time monitoring management, and 3) Adequate decision support. This research strives to tackle the conventional challenges of PHC.

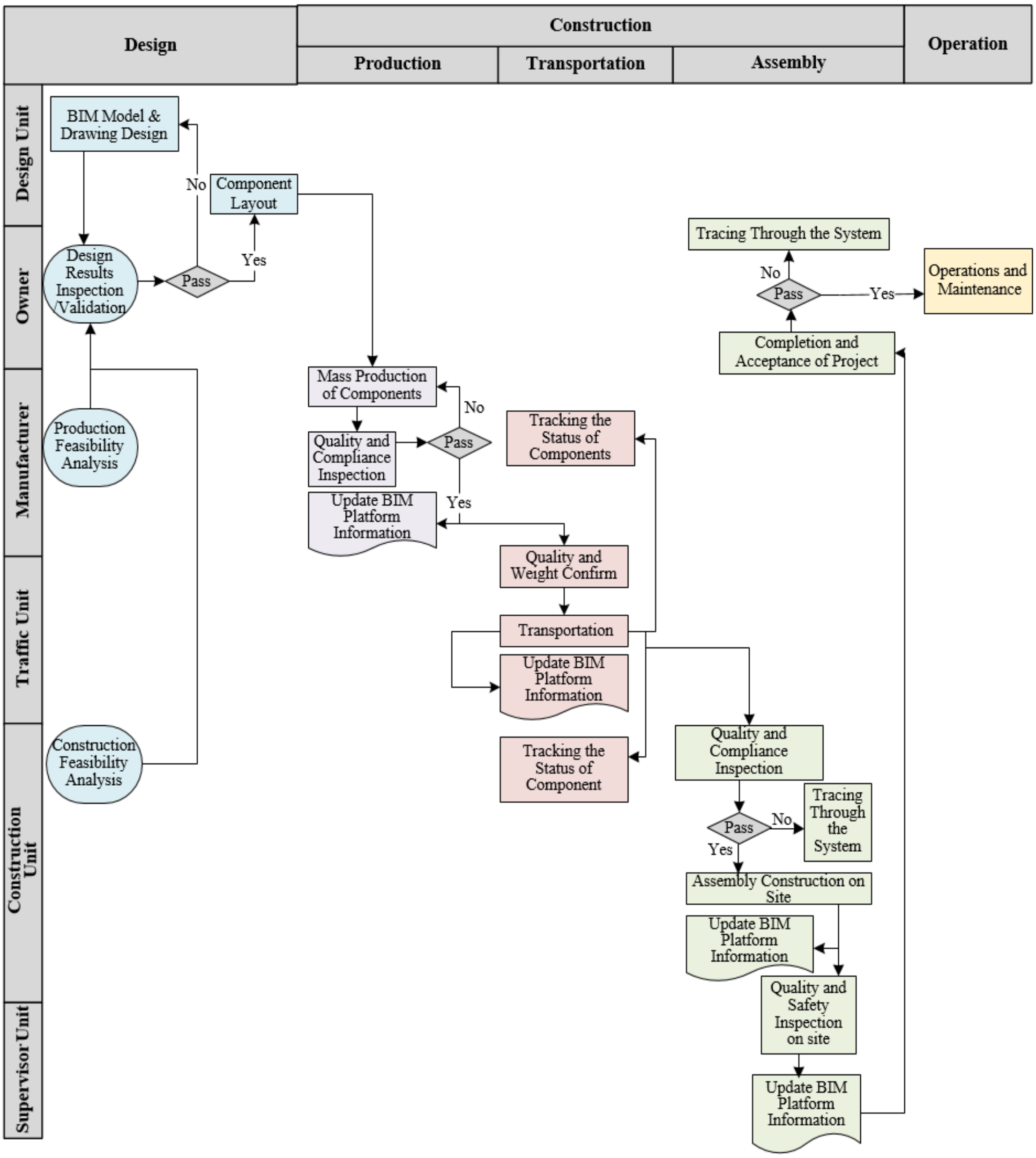

Fig. 6. Flowchart of the intelligent platform based on the typical PHC

1)Effective information interaction. There is no doubt that discontinuity disturbs every chief manager of different PHC phases. Most shareholders in construction are relatively independent, so it is significant to offer a bridge that can capture useful data effectively and then share it in a convenient manner. In this platform, CPS devices collect first-level information, and after sophisticated computing, corresponding data are automatically transformed to specific stakeholders. Its database is built on blockchain technology, which not only contains the principle PHC codes and standards but also gathers valuable data in project management. Consequently, value-added services are easy to provide by integrating massive information from PHC's lifecycle. As for the executives, the PHC's status, schedules, plans implementation, and investments are statistically analyzed, and the production management system provides products-services-bundle solutions to the particular department. Apart from that, this system presents the detailed BIM models through the lifecycle of PHC to assist users in inspecting the position of PCs, mastering the model characteristics, and facilitating the integration and standardized management of PHC.

2) Real-time monitoring management. It is believed that timely data collection leads to reasonable management under uncertain circumstances. The instant and reliable acquisition of information will offer sufficient support to the supervisors. In this platform, aiming to realize the management of PC status and data statistics, essential information, including the project schedules, usage of funds, comparative analysis of various PC projects, and decisions related to macroeconomic regulation, is uploaded into the system in real time to assist SCM. Moreover, every component can be traced, where unique QR codes are generated for each one, thus realizing substantial identification. The designed BIM lightweight architectural models are browsed to help users monitor the project progress intuitively. Associated with the monitoring section, mobile apps are developed to ensure the traceability of PCs at any time, enhance management efficiency, reduce management costs, promote synergy, and limit information losses. As can be seen from Fig. 7, this system uses Cordova technology, which can bring out several advantages in the mobile platform. In detail, Cordova is an open-access mobile development framework with little need for platform-specific development. Thus, it is convenient to run on as many different mobile operating systems as possible to realize the rapid development of cross-platform mobile applications, and it is also compatible with iOS and Android applications. On the other hand, the execution of Cordova relies on standard-

compliant API bindings to access each device’ s capabilities; therefore, modifying the as-built platform at a lower level is less laborious. As a consequence, the PC production data, assembly sequence, and time requirements are obtained to facilitate warehousing and distribution.

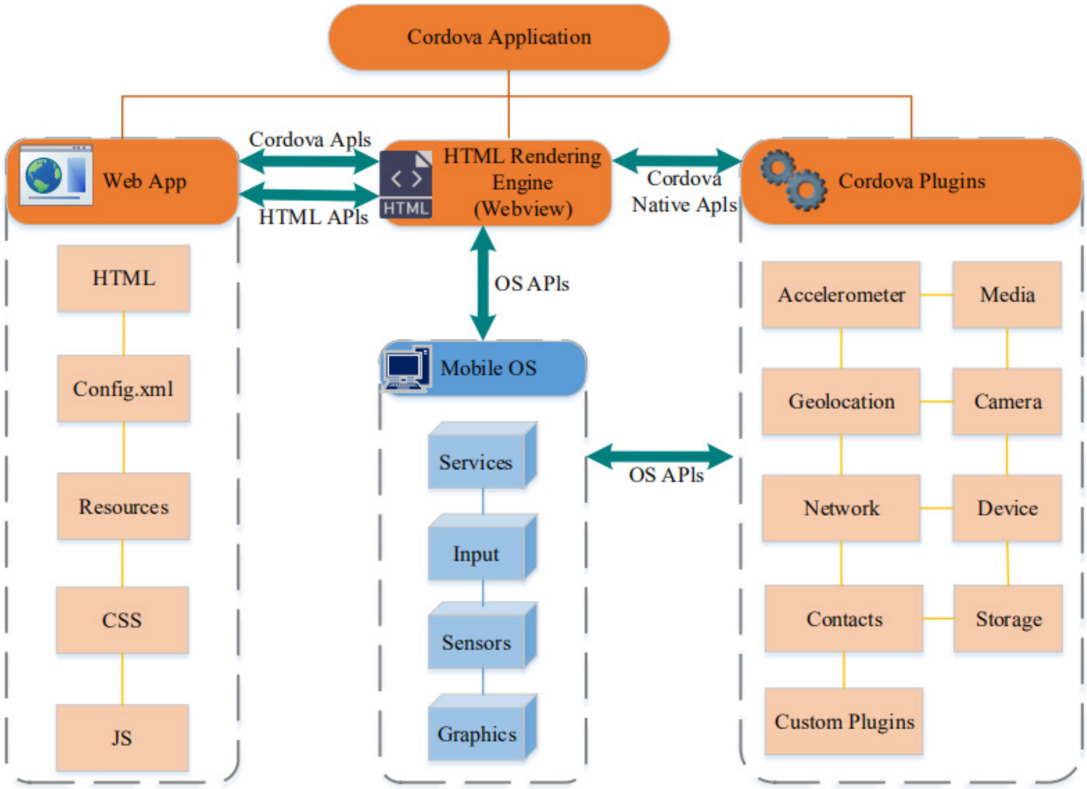

Fig. 7. Diagram of the Cordova technical scheme

3) Adequate decision support. Every scientific, reasonable, and smart decision requires plentiful support in various aspects (Wang et al., 2020). It is crucial for decision-makers to acquire adequate assistance under a dynamic environment (Badi and Murtagh, 2019) in the case of management failure. However, unforeseen disturbances occur frequently in PHC that hamper the timely detection of changes and quick response to emergencies. In this platform, the decision cockpit is involved, where vivid visualization of the project can assist decision-making. Specifically, statistics of PC distribution, completion, implementation, and investment are accurately revealed, and the diverse components’ statuses are represented in visualization with unique colors. In mobile apps (see Fig. 8), this visualization displays the installation progress of the PCs in real time and verifies the rationality of the construction

process; meanwhile, the warehousing information is transferred to the platform, and other personnel can check the status of the PCs through a mobile app, which facilitates more dynamic inventory management. In addition to the real-time traffic information and transport requirements of components available on the platform, the verification results of installation are also revealed intuitively, and the platform can instruct workers on proper assembly if an error occurs.

Fig. 8. The service-oriented process of data collection by mobile apps

4.2 Specialized innovation of servitization system

As there are many links involved in PHC, each link of its supply chain may be affected by disruptions, resulting in depressed reliability. Moreover, given the continually evolving nature of supply chains, our goal is to more fully address supply chain resilience and develop a strategic understanding of PHC demands and supply networks to formulate feasible strategies. Therefore, from the perspective of value co-creation, an innovative combination of cutting-edge technologies is adopted in this platform, and a responsive mechanism is also configured to coordinate the intrinsic requirements of shareholders and dynamic needs by reacting to instant variability, thereby fulfilling sustainability.

1) Intelligent clauses. With the implementation of blockchain, it is plausible to form a smart contract, which is a coded, self-executing agreement between PHC parties on a blockchain. It is intended to facilitate, verify, or enforce contractual obligations by embedding contractual clauses in the computer system and then automating contract execution (Min, 2019). Thus, smart contracts not only make stipulations and criteria based on agreements in the same way that a conventional deal does, but they also enforce those obligations automatically. As consequences, expenditure and transaction time can be reduced since smart contracts can execute themselves. Also, by incorporating IoT into the blockchain, contractual fraud will be easily detected and prevented, thus making the PHC supply chain more resilient. In the platform, with the utilization of smart contracts, it is feasible that the system identifies accountabilities and trigger milestone-based payments could automate agreements; simultaneously, blockchain-enabled applications that aggregate data into a shared project management dashboard could help to manage PHC workflow.

2) Flexible production. The platform establishes a database of PCs and conducts classified management to realize accurate control of inventory demand and supply situation in the upstream and downstream of the PHC supply chain so as to adjust the PC production volume flexibly. Our platform mainly includes: (1) establishing a safety reserve of different types of PCs, which can act as a buffer in the event of an interruption, giving the supply chain time to take action to recover. (2) Maintaining additional production capacity, the standardized production of PCs enables them to obtain supplies from multiple sources and increases the level of inventory sharing with other locations. The platform could ensure the continuous production capacity of PCs through the implementation of information sharing with multiple manufacturers through the database, thus readily achieving smarter decision-

making.

3) Smart transportation. Driver, transportation speed, and route are the significant factors affecting the resilience in the transportation stage. The platform is capable of managing the driver's information and physical status, providing intelligent automatic scheduling to respond to emergencies timely. Besides, vehicle statuses (including speed and position) are monitored during the whole process to avoid the subsequent construction delay caused by improper vehicle operation. As far as the transport route is concerned, if problems occur in the current path, it will automatically switch to another reasonable one to ensure transportation efficiency.

4) Wise construction. If an installation or on-site construction problem happens, the platform will conduct a simulation inspection and identify its source timely, effectively formulating solutions to cope with unexpected risks. Additionally, its intelligent scheduling system is capable of stimulating the productivity of labor forces, explore workers' motivation, and effectively reduce the idling of workers. The precise auxiliary installation function of the platform helps workers to accomplish the accurate installation of every signal PC, which also maximizes the cooperative work of various types of workers.

5. Practical application of the intelligent platform

5.1 Description of the case study from Shenzhen

As the first EPC project in Shenzhen, China, the BaoLan Community is a government-funded indemnification housing project with a total construction area of 253,500 m^2 and 1,622 houses that are divided into eight buildings. Given that the construction time of the project matches the research plan and the project party was willing to use the platform to examine the efficiency, this project (simplified overview see Fig. 9) was selected as a practical case to demonstrate that the SPSS approach was applicable in the construction industry. To collect relevant information, the research team has arranged a series of site visits and meetings with concerned shareholders, including owners, manufacturers, transportation personnel, engineers, and workers, to test the efficiency of the intelligent platform. The project BIM models are automatically analyzed and uploaded to the intelligent platform after lightweight processing, and the project data are automatically gathered and uploaded in real-time.

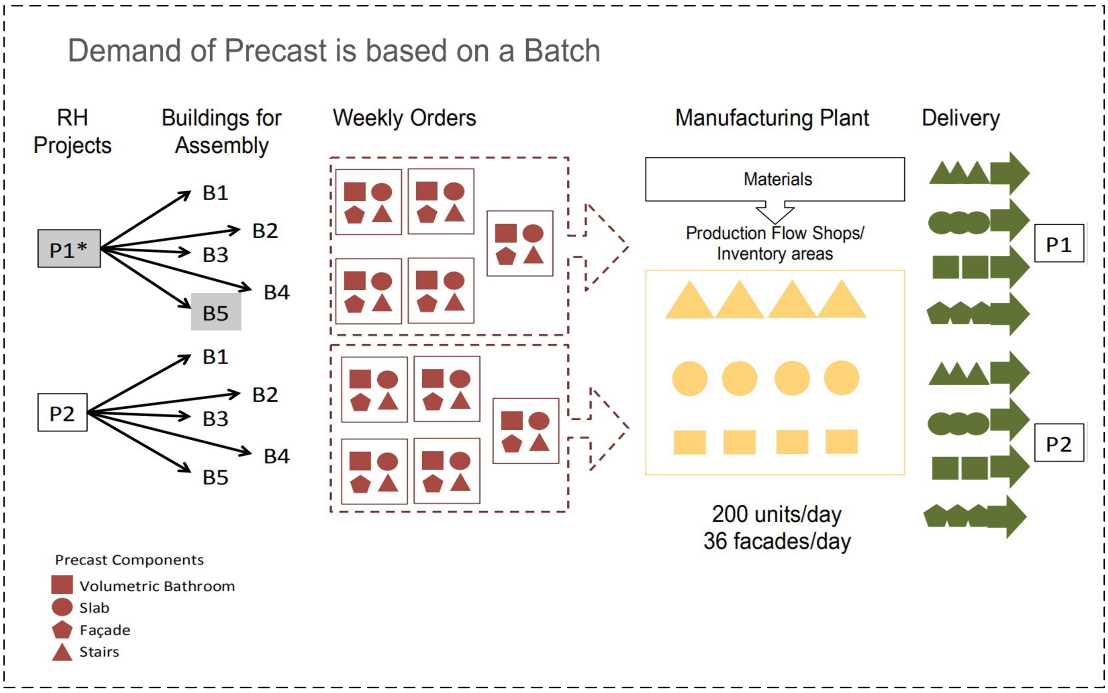

Fig. 9. Practical case of PHC in a simplified illustration

5.2 Functional operation of the platform

5.2.1 Project management service

PHC supply chains evolve so rapidly that sustainability requires continuous collaboration with stakeholders and reviewing and refining data. In this case, with the utilization of the platform, smart contracts are formed through the blockchain, and the integrity of information transfers made by the agreement will be improved with a shared database confirmed by many network shareholders. It is guaranteed that the retrieved data are not corrupted or altered after recording as they can only be read and written by querying and retrieval. Any other operations, such as revision or deletion, are strictly prohibited. The project participants (owner, designer, component producer, transporter, and assembler) use their respective enterprise accounts to log into the platform, and each group has a unique set of system operation rights. Besides, the management cockpit generates statistics on the component distribution, plan implementation, and investment status in each stage. As shown in Fig. 10, the data penetration function is also used to generate real-time components and statistical charts to simplify the operational interface and ensure the richness of the data services.

Moreover, in extreme events, supply chains will not always be resilient. For example, disasters can destroy nodes, separate demand from sources of supply, destroy road networks, or create long-term disruption. Due to various impediments that are predictable, with the application of the platform, each stakeholder can view real-time information about the components, from their design to their installation, and receive visual assistance for the subsequent control, operation, and maintenance processes. In addition, the system also provides solutions for managers in each stage and allows them to inspect data related to project progress and costs that can help them further understand the manufacturing and construction details. By widening the scope of distribution nodes through the platform, administrators can obtain a broader picture of the PHC supply chain. An expanded understanding of the multitude of information provides more robust resilience efforts.

Fig. 10. Project management and data penetration function

5.2.2 BIM model management service

The BIM model has a huge data volume; for instance, a model of a civil structure curtain wall with a floor area of 300 thousand m^2 consumes 1.7 Gb. In this case, direct transmission resulting in a large amount of data corresponds to poor efficiency and high hardware equipment and network bandwidth requirements. Therefore, a lightweight BIM model is indispensable. Targeted data compression and reduction techniques can reduce the original model size by approximately 85%. Besides, this technique also allows the BIM model to move from traditional desktop software to web and mobile terminals without being limited by the browser. Additionally, the combination of BIM and CPS technology transfers the needs of parties from offline to online applications, which enhances the resilience of the BIM application significantly.

In this project, after receiving necessary project information, the design unit starts to design and typeset the model before uploading the model files into the system. By lightening the model, the system automatically reads the contents of the data and sends them to the stakeholders in the other stages for subsequent works. In the model management service of the platform, the BIM model can be browsed (see Fig. 11) by a single building, floor, component type, component multi-level, and multi-perspective using Internet Explorer and a mobile app. Meanwhile, viewing the model of the project can visualize and monitor the real-time progress of the construction. Furthermore, different colors represent the various states of each component. For instance, transparency indicates that the component is assembled, whereas red color indicates that the component has not been produced. In the real-time visualization of project progress, when a user clicks a floor in the BIM model, he or she can obtain detailed information about its components, including design, status, schedule, and cost.

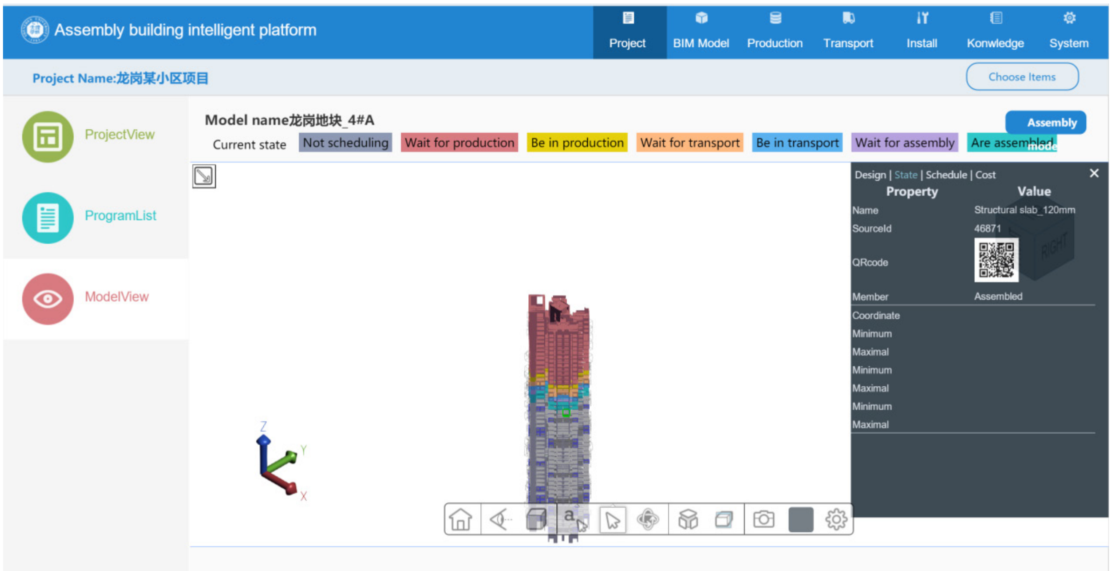

Fig. 11. Function for progress and details visualization

5.2.3 Production management service

Production management service aims to fulfill the smart production by employing CPS and IoT, which involve production component state, production schedule, production execution, and production investment. In the blockchain, each stage of a sub-contract takes the form of an intelligent contract, which can be converted into programs and codes, then copied and stored in the processing system, and monitored by the system network running blockchain. Consequently, the bill of quantities and BIM model of PCs, which act as the fundamental performers to resources organization, can be obtained to ensure a smooth production process.

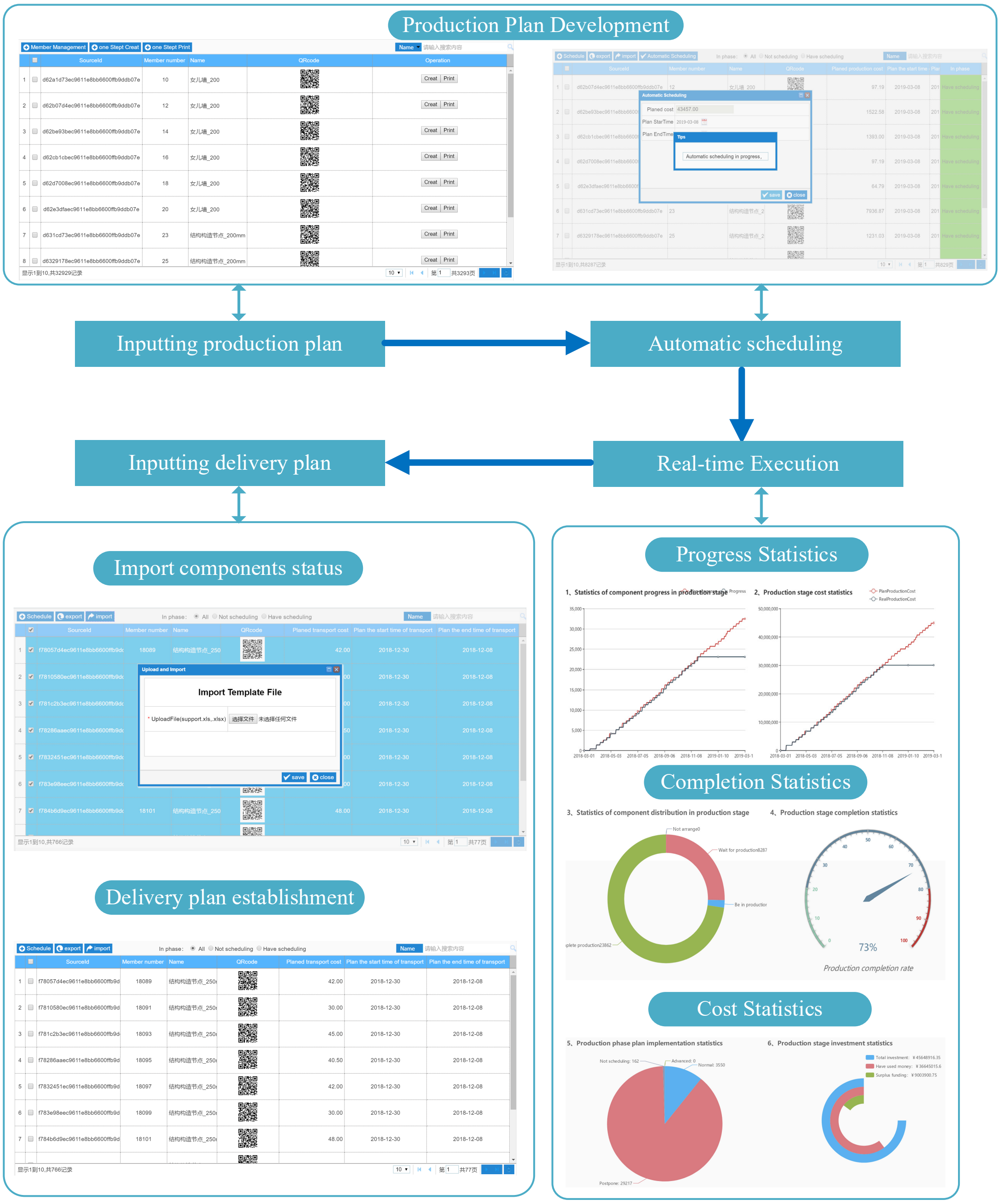

Fig. 12. Working logic of production management service

Furthermore, once production nodes are exposed to various disturbances, recovering to a reasonable running level to meet fundamental manufacturing requirements in the immediate repercussions should be prioritized in production-involved supply chains. As depicted in Fig. 12, the planned and actual statuses are reviewed in each phase of the project; by clicking the cost statistics line graph of a node at a certain period, it displays detailed information, including the current sub-item investment proportion and total funds used. Once production is completed, the platform generates QR codes correspondingly, where each component associated with these QR codes can be uniquely identified. In the blockchain, the unique QR codes on each PC makes it permanently traceable, and it is also used for construction guidance. The production progress of components can be visually displayed by using BIM technology, the production of components is tracked and managed by QR codes, and the production information, current status (unscheduled, to be produced, in production, and completed) of components are recorded, thereby providing solutions for the production department. If any disturbances occur, taking the supplier's inability to produce on time as an example, alternative vendors can support them quickly due to every supplier being centralized in the platform's standard BIM database. Just-in-time resupply adaptability may mitigate short-term breaks in the supply chain.

5.2.4 Transportation management service

In SPSS, transportation acts as a key player in connecting supply and construction nodes, realizing a transparent, sustainable, and efficient status-data flow among them. To effectively execute logistics planning, the platform should examine known and potential hazards plotted along the supply chain, alternate routes, and any known transportation restrictions. As a vivid illustration of Fig. 13, after receiving the orders, the delivery schedule and driver-apportion can proceed automatically; real-time monitoring is also realized on the whole transportation stage. Moreover, the unloading of machinery, movement of vehicles within and outside the route, and location of the stacking site can be planned to avoid vehicle congestion and other problems. As drivers often rely heavily on information technology and communications to direct their movements and deliveries, the merit of intermodal transportation networks is that traffic requirement can be shared and transferred from one scheme to another if disruption happens (Zhou et al., 2019a).

The continually evolving nature of supply chains means the data captured throughout this process can change quickly. In this stage, blockchains can be used to prevent security flaws while enhancing transportation connectivity and delivery services. Besides, the platform can produce real-time statistics on the investments in the transportation stage and visualize the costs. If the funds of transportation components show a wider margin of variation, the platform will urge managers to conduct inspections and make appropriate adjustments. Additionally, the components may be damaged due to the bumping of vehicles and other inappropriate operation in the moving processes. Information and images (e.g., components status, driver information, routes) are stored, thus the causes of such problems and the responsible persons can be traced through the system immediately.

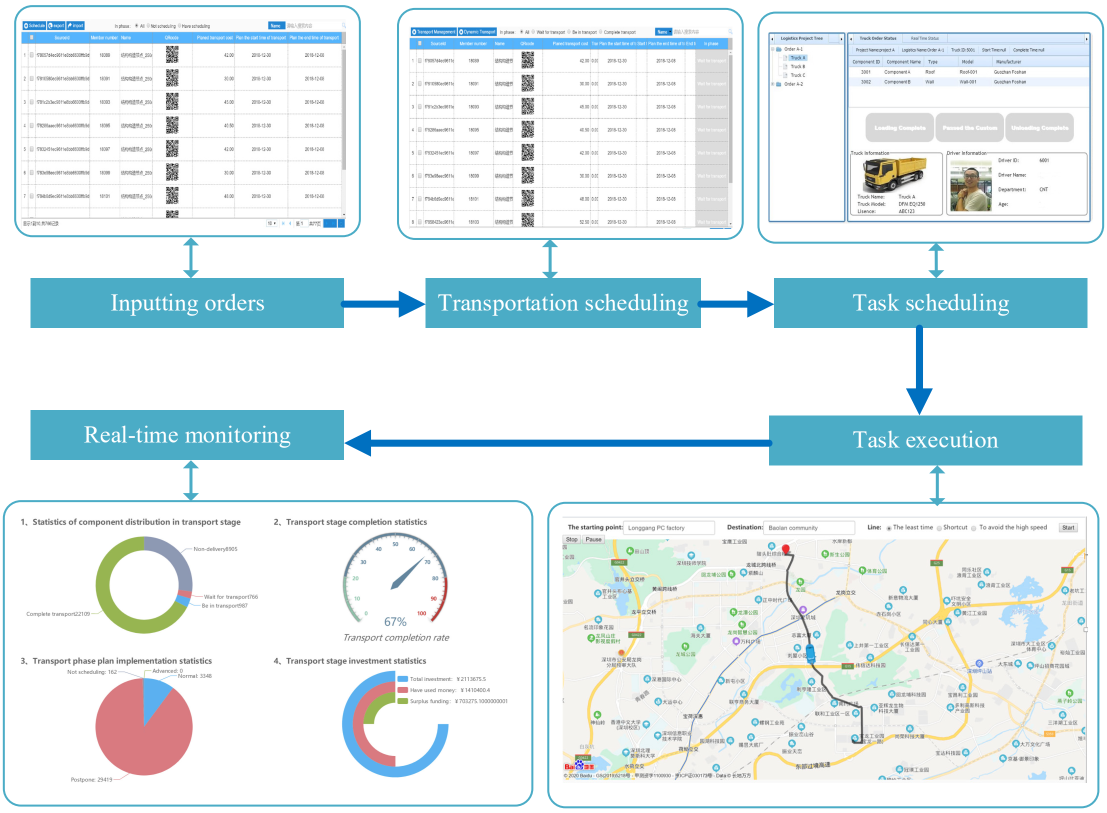

Fig. 13. Workflow of transportation management service

5.2.5 On-site assembly management service

As depicted in Fig. 14, the developed on-site assembly service plays a significant role in construction operations, inspections, and supervision in PHC sites. For construction operations, when the PCs are transported to the sites, the on-site manager launches the QR code scanning function to complete the warehousing registration. The platform is used to realize the optimal assignment of assembly tasks by allocating them to appropriate workers; thus, workforce management and effective construction can be optimized immensely. For inspections, given that the diversity and complexity of PCs may enable workers to install them in the wrong place or in an inappropriate manner, this platform can offer useful instruction through mobile apps while detailed information is embedded in QR codes. Moreover, inspection after assembly can be conducted in meters by GPS, which ensures individual deviation incapable of exceeding the reasonable tolerance. For supervision, order databases, including production orders from factories and delivery orders from transportation firms, are connected to this system; thus, dynamic coordination can be achieved due to real-time data collection through QR code scanning by workers. In addition, with the utilization of BIM, reality presentation is realized to monitor and visualize real-time construction progress, thereby reducing schedule delay. Such hazardous behaviors can be recognized and alerted prior to happening. Therefore, every involved shareholder can be aware of the ongoing construction status and make corporate modifications or decisions collaboratively. As a consequence, if sudden risks disturb the PHC supply chain, it will be more resilient in coordinating emergency preparedness plans and actions.

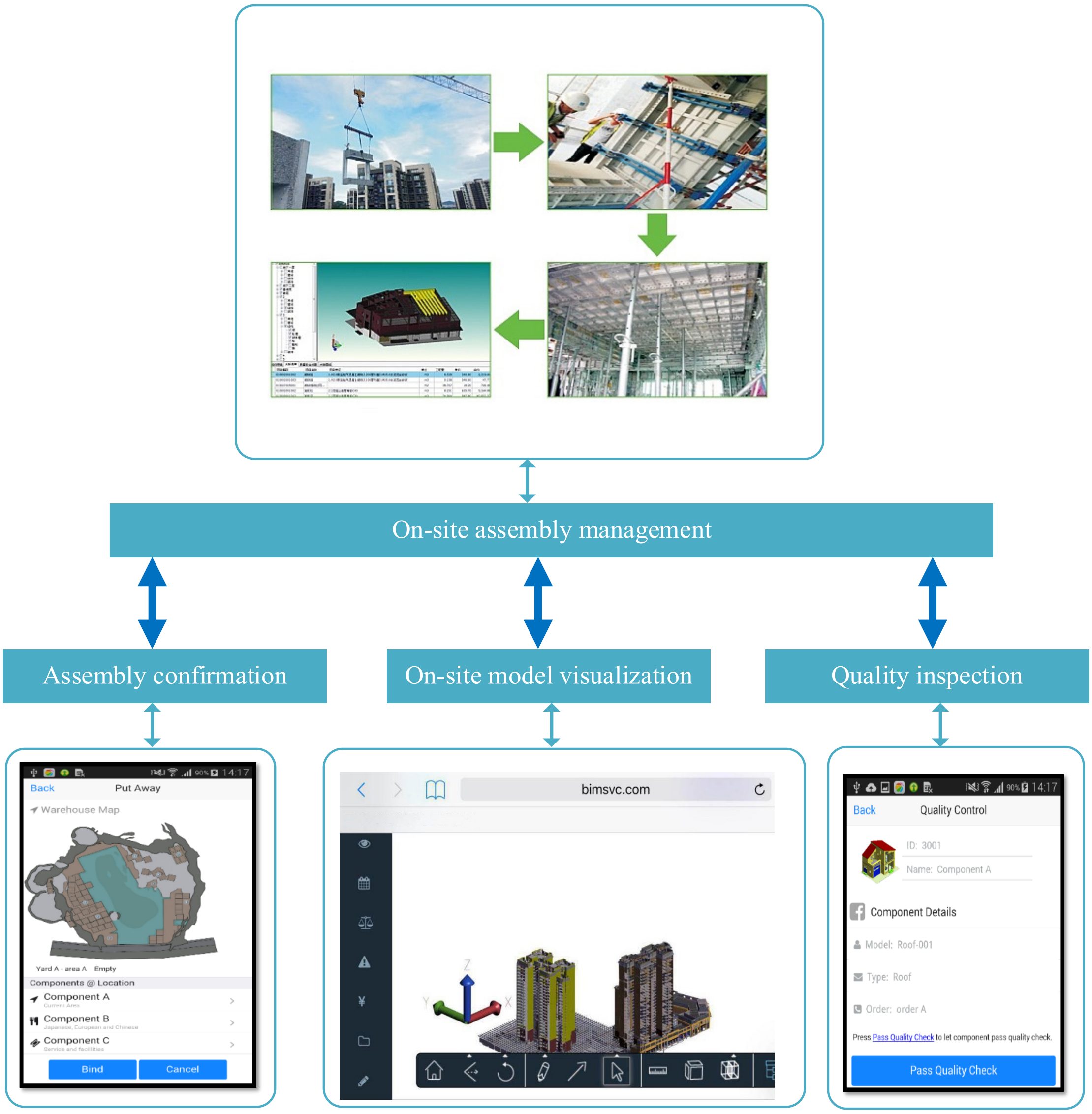

Fig. 14. Operation logic of on-site assembly management service

5.2.6 Knowledge management service

The PHC needs to go through multiple stages, and the engineering data is gradually clarified and detailed through each of these stages, thereby generating a large amount of data. Moreover, large-scale disruptions can significantly diminish effective information transmission; hence, considering the utilization of blockchain, the data in the base is strictly encrypted and guaranteed to be authentic, which not only promotes the value of data sharing in the supply chain but also improves the ability to resist risks in the SCM. The database must maintain data integrity so as to authentically notify various shareholders on the progress and any existing problems or obstacles; in this case, the engineering database allows temporary, inconsistent data to exist and be managed. As illustrated in Fig. 15, the knowledge base provides various collection, maintenance, and retrieval functions for relevant materials, including the production and installation of components, process methodologies, and technical standards, where concerning staff could consult its relevant expertise to alleviate a lack of valuable information in an emergency.

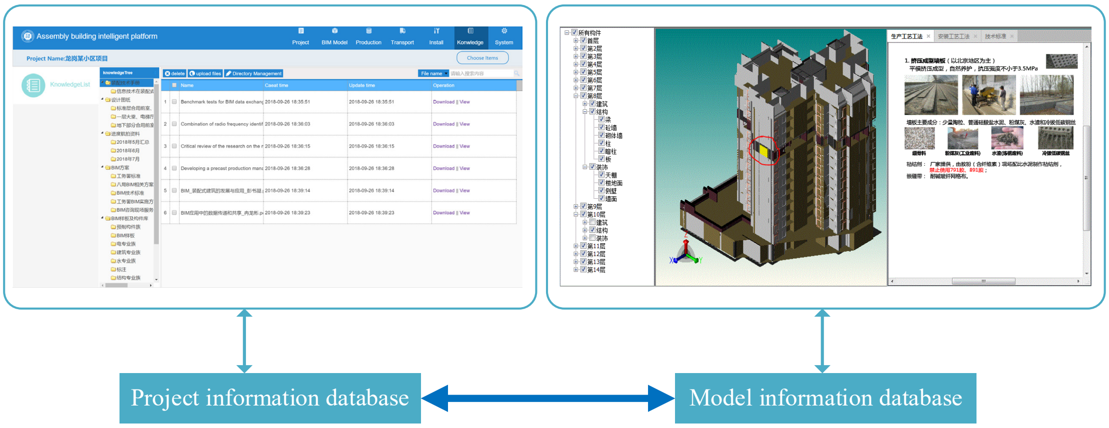

Fig. 15. Data and knowledge service for value sharing

5.3 Discussions

Reviewing the practical implementations of an SPSS approach in the case study, the main benefits of the proposed platform can be summarized as follows. 1) Sustainability enhancement, where the platform can be seamlessly integrated with the PHC supply chain to enable the sharing and synchronization of information throughout the lifecycle. Specifically, no matter which phase encounters unexpected interruption, the platform is committed to alleviating the effects of disruptions and avoiding long-term failures. 2) Lean construction, by utilizing blockchain in addition to realizing the traceability of PCs, performs classification authority and security assurance based on the smart contract. 3) Timely interaction and convenient access. With the real-time feedback and visualization achieved in the platform, real-time costs in every stage can be visualized to help the relevant staff in making the appropriate modifications. Furthermore, it is feasible to identify any current or potential barriers, such as schedule delays, labor shortages, or incorrect installation.

However, several problems are encountered when actually using the platform. Firstly, the capacity issue must be considered, as operating multiple projects at the same time may limit the server capacity. Secondly, the QR codes may fail to respond in harsh conditions, even though production factories have tried to protect the tags. Finally, as PHC involves various stakeholders, only by enabling all personnel to use the platform quite proficiently can the platform play its superior role to the maximum.

6. Conclusion

The recent years witnessed the booming development of ICT, which motivated the construction industry to explore the profound revolution in a sustainable manner. PHC cannot serve as an eligible contributor unless alleviating the absence of process continuity, poor interoperability among heterogeneous stakeholders, insufficient visibility, and traceability of real-time information. With the adoption of the SPSS strategy, a blockchain- and IoT-based, BIM- and CPS-enabled platform has been exploited to intensify the sustainability of PHC. The major contributions can be summarized into three aspects:

1) The proposed platform has triggered significant leverage of massive data generated from physical instruments and various users by taking original gathering, precious adaptability, refined processing, and intelligent services into the overall consideration. Hence, literal/graph/BIM data are performing as reliable supporters in sustainable PHC.

2) The hybrid of ICT has facilitated the smarter decision-making process, where effective real-time monitors in schedule/cost/labor/status are achieved. The prefabricated components are defined as the smart connectivity products in IoT- and CPS-enabled circumstances, while blockchain is favorable to prevent injecting or relaying pernicious information in communication, which better handles the dynamic changes of construction stages.

3) The SPSS approach exerted impacts on settling sustainability issues, where shareholders were actively involved in lifecycle value co-creation by offline manners (construction operations) or online channels (platform or mobile apps), and resources. Also, connected services embraced its maximum values in lean construction.

SPSS is an ecosystem-centric view of open innovation that harnesses edge ICT. As the explorative research, though this proposed platform still in infancy, the feasibility of boosting sustainability based on SPSS innovation has been demonstrated. Open insights and further discussions are invited from researchers. For future studies, the authors recommend the following: 1) from the perspective of interaction, it is relevant to make functional modules more resilient to context-awareness in an autonomous manner, and multiple users and SCPs from other systems can interact closely, where specific needs will be more precisely matched, and 2) from the perspective of value co-creation, since construction and demolition waste still act as major barriers in sustainability, establishing a way to extend the lifespan, improve resource efficiency and circular economy is crucial and imperative.

Acknowledgements

This research was supported by the Humanities and Social Sciences Foundation of the Ministry of Education of China (Grant No. 18YJCZH090), National Natural Science Foundation of China (Grant No. 71801154 and No. 52078302), National Natural Science Foundation of China (Grant No. 71801159), Science Foundation for Youth Scholars of Shenzhen University under grant 2019070 & 189692, the Natural Science Foundation of Guangdong Province of China (Grant No. 2018A030310534), and the funding support from Shenzhen Science and Technology Innovation Commission (Grant No. JCYJ20190808174409266).

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