BLOCKCHAIN-BPMN INTEGRATED FRAMEWORK FOR CONSTRUCTION MANAGEMENT

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ABSTRACT: *Implementing blockchain benefits various construction management processes, such as securing payments, enabling traceable design process, and enhancing information transparency in supply chain. However, blockchain implementation in construction is still in its infancy due to weak functionality of smart contracts, which are self-enforceable programs allowing iteration between external data and blockchain. In the context of construction management that embraces complex and dynamic business processes, smart contracts are currently designed based on specific and isolated functional requirements without considering the connection and execution logic between these functions. It leads to inefficient collaboration and even execution errors, thereby corrupting data quality and even causing business failure. Therefore, this paper proposes a Blockchain-BPMN (Business Process Model and Notation) integrated (BBI) framework for construction management. The framework poses two contributions. First, a BPMN-driven method is developed to design smart contracts supporting executing linked and logically connected business activities. Second, an access control strategy is integrated into smart contracts to safeguard the accessibility of sensitive business data in a blockchain environment. The BBI framework is validated in an actual BIM design collaboration scenario, and results show its feasibility and computational performance are acceptable. Several aspects for improvement and future directions are discussed in the end.*

KEYWORDS: *Smart contract; Blockchain; BPMN; Construction business process*

1. INTRODUCTION

Data security is becoming an increasingly concerning issue in the construction industry. With the higher level of digitalization in construction, it is inevitable that data security becomes more important (García de Soto et al., 2022). Several examples highlight the vulnerabilities that exist in the construction business process, such as the lack of records for Building Information Modeling (BIM) changes, fragmented and unaccountable supply chains, and insecure payment systems. These vulnerabilities can result in various negative consequences for construction projects, from delays and cost overruns to compromised safety and quality. Therefore, it is crucial for the construction industry to prioritize data security, traceability, and process automation. By implementing robust security measures, ensuring transparency and accountability in the supply chain, and automating processes, construction companies can mitigate the risks associated with data breaches and cyberattacks. This not only protects sensitive information but also improves overall project efficiency and reduces the likelihood of errors and disputes. The construction industry must recognize the importance of data security and take proactive steps to safeguard their systems and information.

Blockchain and smart contracts have emerged as potential solutions to various challenges in different industries, including the construction sector. Blockchain is a decentralized digital ledger that records and verifies transactions across multiple computers, ensuring transparency, security, and immutability (Leng et al., 2022). On the other hand, smart contracts are self-executing contracts executed in the blockchain platforms with the terms of the agreement directly written into lines of code (Ye et al., 2022a). These two technologies have the potential to revolutionize the way transactions are conducted and contracts are executed.

In the construction industry, blockchain and smart contracts have been explored as solutions to various problems. One example is payment management. Smart contracts can automate the payment process, ensuring that contractors and suppliers are paid promptly based on predefined conditions (Sigalov et al., 2021; Ye & König,

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2021a; Ye et al., 2020). Another example is in the field of BIM change record in the design phrase. By implementing smart contracts, any modifications to the design of BIM model can be automatically updated to blockchain, ensuring that all stakeholders are aware of the changes and can plan accordingly (Xue & Lu, 2020). This can help streamline the design phase and minimize the risk of errors or miscommunication. Supply chain management is another aspect of the construction industry that can benefit from blockchain and smart contracts. With complex supply chains involving multiple suppliers, contractors, and subcontractors, ensuring transparency and traceability becomes crucial. Blockchain can provide a secure and immutable record of every transaction and movement of materials, enabling stakeholders to track the origin, quality, and location of construction materials, where smart contracts can automate the procurement process, ensuring that materials are ordered and delivered on time, and payments are made only after satisfactory delivery (Elghaish et al., 2023). Therefore, blockchain and smart contracts have the potential to revolutionize the construction industry by addressing various challenges and improving efficiency. As more research and implementation examples emerge, these two technologies are not just buzzwords but practical solutions that can drive innovation and transformation in the construction industry. However, the current smart contract implementation is isolated, neglecting task sequence execution, leading to limited automation. Furthermore, the use of code in smart contracts makes them challenging to understand for non-programming participants in the construction industry.

Therefore, the main objectives of this study are to explore the possibility of incorporating blockchain and smart contracts into construction business processes and to improve the automation level using smart contracts in the construction field. To achieve these, we propose a novel BPMN-driven approach aimed at enhancing the efficiency and automation capabilities of smart contracts. The study aims to develop a Blockchain-BPMN integrated framework for connected smart contract execution, enabling seamless interaction and collaboration among different smart contract functions, thereby automating complex construction workflows. Additionally, a smart contract access control strategy is proposed to manage data accessibility, ensuring that sensitive information is only accessible to authorized parties while maintaining transparency.

2. LITERATURE REVIEW

2.1 Blockchain and smart contracts in construction

In the construction industry, many blockchain and smart contract reviews were conducted and their adoption to the construction industry were highlighted. For example, the applications of blockchain and smart contracts in construction were summarized by Li and Kassem (2021), which mainly focusing on information management, payment, procurement and supply chain management. Another smart contract review was conducted, which pointed out that 81 smart contract-related papers were published from 2014 to 2021 in the construction industry, focusing on the areas of contract and payment, supply chain and logistic, and information management (Ye et al., 2022a).

One of the critical pain points in the construction industry is the inefficiency and lack of transparency in payment processes. Smart contract-based payment systems have emerged as a promising approach to tackle these issues. Ahmadisheykhsarmast and Sonmez (2020) investigated the implementation of smart contracts in construction projects to enhance security in payment processes. Their study demonstrated that smart contracts could automate payment release based on predefined conditions, reducing payment delays and disputes significantly. Building Information Modeling (BIM) is a critical component of the construction process, allowing stakeholders to collaborate visually and efficiently during the design phase. Integrating blockchain technology with BIM has the potential to enhance data management and collaboration (Ye et al., 2022b). Tao et al. (2021) explored the use of blockchain and smart contracts for BIM-based collaborative design in construction projects. Their research demonstrated that the decentralized and immutable nature of blockchain improves data sharing and coordination among stakeholders during the BIM design phase.

The current use of smart contracts faces limitations, including their isolated nature and the absence of a coherent approach to developing logical methods that align with construction business processes. In Fig. 1, a comparison highlights the difference between the current practice and the potential capabilities of smart contracts in construction workflows. Presently, various tasks are handled by independent smart contracts, necessitating users to determine which contract to engage. For instance, in Fig. 1(a), tasks are individually managed by separate smart contracts without intrinsic connections, which may cause execution or business logic errors and decrease the automation level of smart contracts. The current practice contrasts with practical expectations where inter-dependencies should be embedded. Fig. 1(b) illustrates the expectation for execution tasks within a smart contract, which enhancing the automation potential of smart contracts.

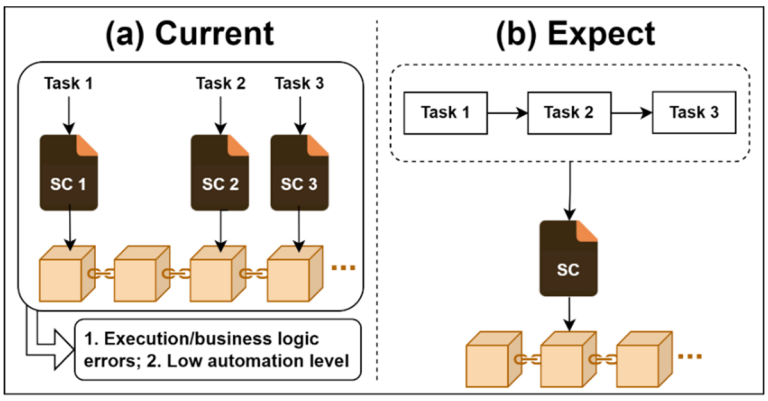

Fig. 1: The limitation of the current usage of smart contracts. (a) Current practice of smart contracts; (b) Expected usage of smart contract

2.2 Combination with BPMN for construction business process management

Business Process Model and Notation (BPMN) is a standardized graphical representation language used to define and visualize business processes (Object Management Group, 2013). In the realm of construction project management, BPMN offers a range of benefits. It provides a clear and intuitive visualization of complex construction workflows, enabling stakeholders to understand processes more easily (Borrmann et al., 2018). This enhances communication, collaboration, and decision-making among project teams. Furthermore, BPMN can facilitate the identification of bottlenecks, inefficiencies, and potential improvements in construction processes, contributing to more effective project management and resource allocation (Borrmann et al., 2018).

BPMN's suitability for connecting smart contracts is noteworthy. With its versatile graphical representation, BPMN can model and illustrate the interactions between different smart contract functions effectively. This enables the design of intricate sequences of smart contract executions, facilitating the automation of multi-step processes (Ye & König, 2021b). For example, López-Pintado et al. (2019; 2022) introduced and implemented a blockchain-based BPMN execution engine called Caterpillar to generate smart contracts using a BPMN-to-solidity compiler. Di Ciccio et al. (2019) proposed an approach to translate from BPMN process models to smart contracts using Caterpillar tool, execute processes through smart contracts, and track activities in the Ethereum blockchain. The other existing study in the construction industry analyzed the possibilities of combining blockchain and BPMN choreographies, and proposed a framework to identify the state of each process in BPMN processes and choreographies (Spalazzi et al., 2021). Additionally, BPMN can be coupled with access control mechanisms, ensuring that only authorized parties can engage with specific smart contracts or process steps. This integration strengthens security and transparency, both crucial aspects in the construction domain.

However, the current research focuses on direct translation from BPMN to smart contracts, without considering the real-time connection and visual execution of BPMN and smart contracts. One reason is the relative novelty of blockchain and smart contract adoption within business processes. As a result, the exploration of BPMN's capabilities for this purpose is limited. Moreover, incorporating access control mechanisms in this context presents challenges, as construction projects involve various stakeholders with differing levels of authorization. Balancing data visibility and access becomes intricate, given the diversity of involved parties and the need to maintain data integrity and security.

This paper addresses these gaps by presenting two significant contributions. Firstly, it introduces a groundbreaking Blockchain-BPMN integrated framework designed for the connected execution of smart contracts. This framework allows for the seamless interaction and execution of interconnected smart contracts, enabling the automation of complex construction workflows. Secondly, the paper proposes an innovative smart contract access control strategy that caters to the diverse data visibility needs of various stakeholders in the construction process. These contributions collectively aim to revolutionize the construction industry's approach to business process automation, improving efficiency, transparency, and collaboration through the integration of BPMN and blockchain-powered smart contracts.

3. METHODOLOGY

The research methodology, illustrated in Fig. 2, comprises three key steps. Step 1 involves designing a Blockchain-BPMN integrated (BBI) framework by firstly defining the framework's logic and workflow, and then explaining how the connected smart contracts are executed in the framework. Step 2 focuses on developing a strategy to control data access. This includes determining who can see which data level based on permissions and setting rules for accessing data stored both inside and outside of the blockchain. In Step 3, the logical smart contract algorithm is developed, by defining the mapping from BPMN to smart contracts, and developing the smart contracts based on the BPMN execution logic. The output of Step 1 is a concept explanation of the BBI framework, and its functionalities are detailed further by the development of the data access control strategy in Step 2 and the logical smart contract algorithm in Step 3. Step 4 tests the feasibility of the BBI framework using a case study. This includes building and putting the BBI framework into action, and then assessing its effectiveness using a BIM-based design collaboration scenario.

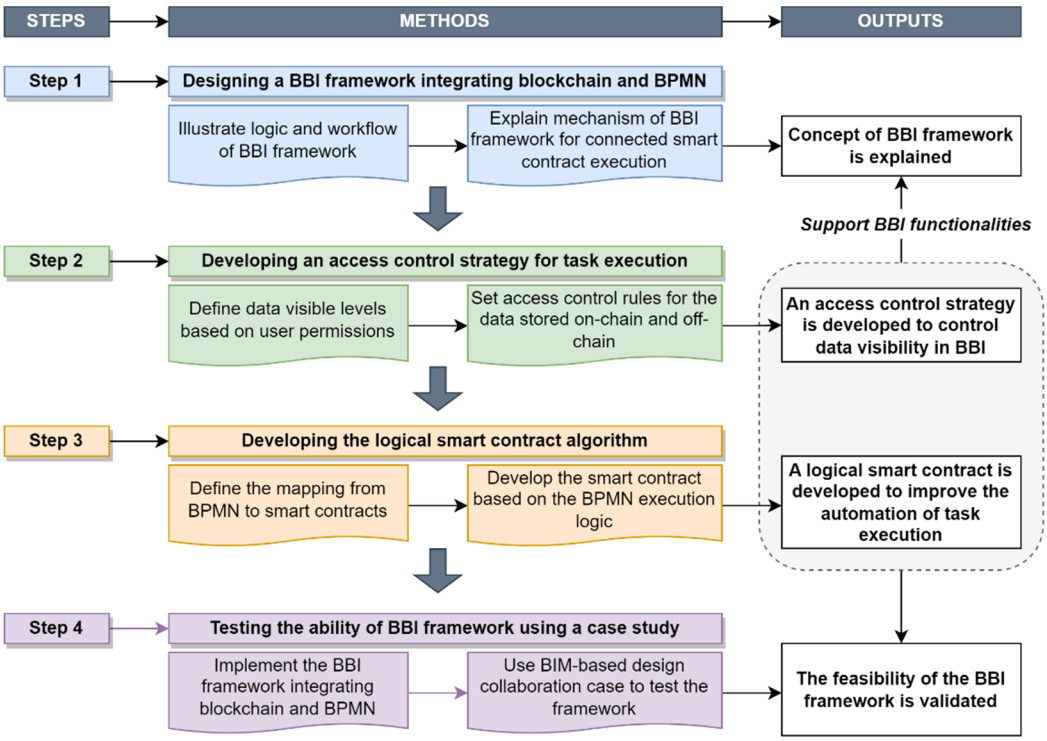

Fig. 2: Research methodology

3.1 Blockchain-BPMN integrated framework

The overview of the proposed BBI framework is shown as Fig. 3. Process-embedded smart contract list (PeSCL) is proposed in this paper for storing all the process-required data in a construction project to be executed via the smart contracts, which includes such as project information, participant information, process units, and the linkage to the BIM model. The PeSCL and the BIM model are the inputs for the framework (Fig. 3①), where BIM model is displayed in a BIM viewer, and PeSCL is displayed as table. They are linked via the GUID of each BIM elements that stored in the PeSCL (Fig. 3②). These two input data are further linked with the construction business process, which is represented by BPMN (Fig. 3③). Each BPMN task is mapped to a corresponding smart contract function. Real-time process visualization and execution are then realized (Fig. 3④). During the task execution, an access control strategy is developed for controlling different data permissions for different participants of the construction project. Such strategy controls the visible level of both on-chain and off-chain data (Fig. 3⑤). The logical smart contracts automatically execute the tasks represented via BPMN with their execution logic, and their transactions are stored in the blockchain (Fig. 3⑥). Such framework can not only visualize BIM and real-time construction business process execution status with an improvement of business process automation, but also build trust and realize data access control.

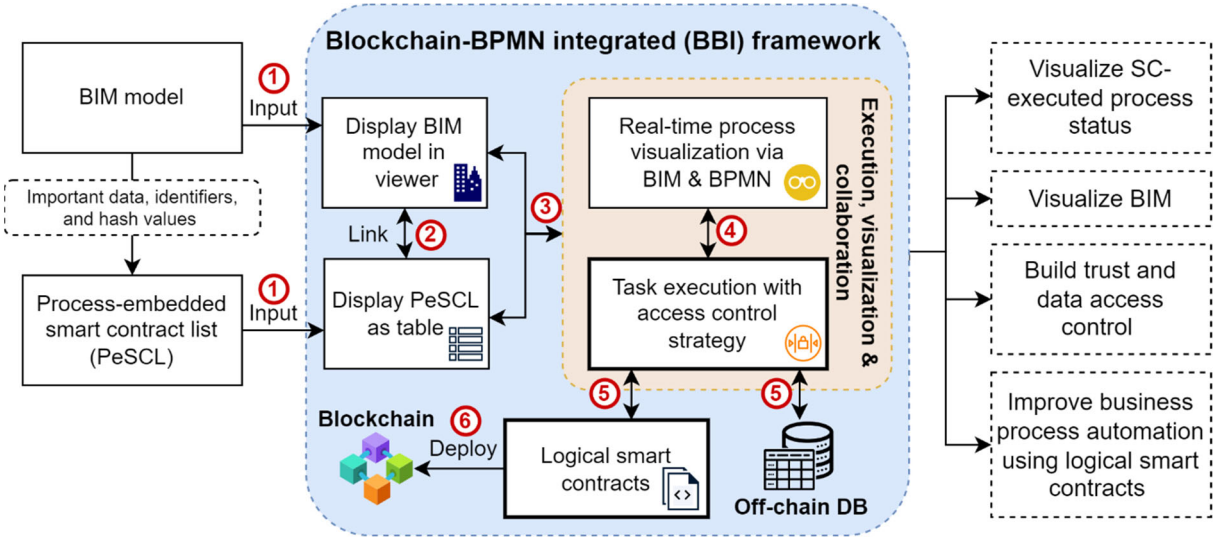

Fig. 3: The overview of the proposed Blockchain-BPMN Integrated (BBI) framework

3.2 On-chain and off-chain access control strategy

The access control strategy can be divided into two parts, namely on-chain and off-chain data access permission (see Fig. 4). All the project-related documents are stored in the off-chain storage, where the permission level of each document is also stored. When users request to check or modify the off-chain data, their username (as identifier) and permission level will be firstly checked. All the sensitive or valuable data are stored on-chain (i.e., on the blockchain), and only specific user can call specific smart contract functions. When users request to view or modify the blockchain (BC) data, their BC account identifier will be firstly checked in their called smart contract function for viewing or modifying request. Further detailed example about the access control strategy is shown in the case study section (Section 4).

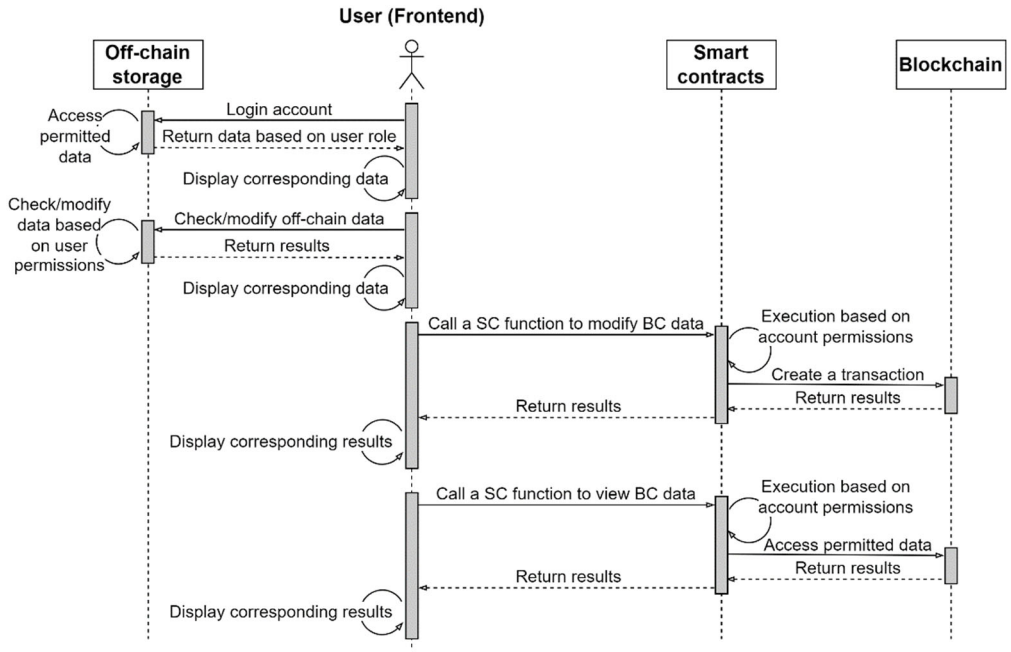

Fig. 4: Access control strategy among users, smart contracts, blockchain, and off-chain storage

3.3 From BPMN to logical smart contract

To solve the problem of current isolated smart contract usage, this paper proposes a way of implementing smart contracts, which is defined as logical smart contracts. Such logical smart contract, which is interpreted based on the BPMN components, not only automates the BPMN tasks based on the execution logic in BPMN, but also further automates the inner actions of some specific BPMN tasks. The mapping from BPMN to the logical smart contract is shown as Fig. 5. In BPMN, there are three main components, namely participants, tasks, and flows. BPMN participants are interpreted into P.StateVariables and P.Modifiers, where the former is used to store the information of the participants (such as identifier and role) and the latter is used to restrict that only specific participant can execute specific smart contract function (for access control strategy). BPMN tasks include task participants and inner actions, where the former is from the BPMN participants with the specific task execution permission and the latter is to indicate what actions could be done within the tasks. BPMN flows are used to indicate the execution logic of BPMN tasks, which is further interpreted into F.StateVariable, Enum, F.Modifiers and F.Functions. Further example of the generated logical smart contract is shown in the case study.

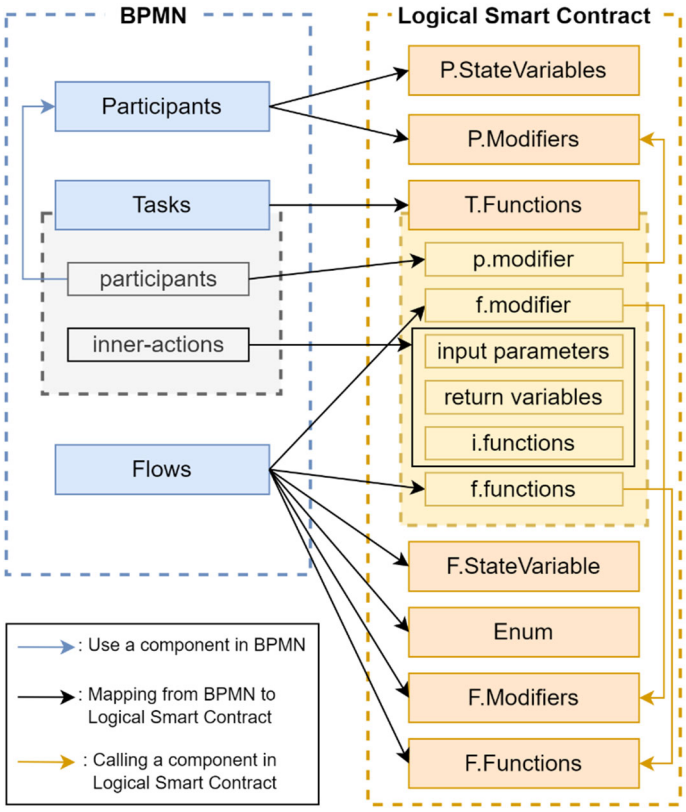

Fig. 5: Mapping from the logic of BPMN to the logical smart contract

4. CASE STUDY

Validation of the proposed BBI framework was achieved through the implementation of a decentralized application, where a React frontend was seamlessly integrated with the Ethereum blockchain. This implementation was rigorously tested against a real-world BIM design collaboration case from Tao et al. (2021). In Fig. 6, the comparative analysis between their original smart contract solution and our enhanced logical smart contract is presented, revealing the improvements achieved by integrating process logic into the smart contract. Following this comparative analysis, the testing results of the case within our implementation are diligently presented in Fig. 7, providing a comprehensive view of the real-world applicability and efficacy of our proposed framework.

In Fig. 6(a), the BPMN workflow was meticulously designed based on the case elucidated by Tao et al., encompassing three distinct roles of participants and a comprehensive set of seven BPMN tasks. Fig. 6(b) depicts the original smart contract solution, which was rather limited, accommodating only two smart contract functions, namely UPLOAD and INQUIRE. In this solution, real-time process status updates were unavailable to participants,

and the execution of smart contract functions required manual intervention from the participants themselves, lacking the seamless automation sought after. Conversely, in Fig. 6(c), our proposed logical smart contract solution represents a significant advancement. Execution logic and access permission are ingeniously incorporated directly into the smart contract, improving its ability for automation and collaboration. Furthermore, execution permissions are elegantly restricted by this design, significantly mitigating the potential for errors and associated challenges, thus providing a more robust and efficient solution for BIM design collaboration in the smart contract system.

Fig. 7 serves as a comprehensive visual representation of the final case outcomes, encapsulating a multitude of crucial components that harmoniously contribute to the success of our BBI framework. Within this illustrative figure, Fig.7(a) provides an immersive real-time visualization of the BPMN process status, meticulously denoting task execution through distinct markers, with yellow indicating completed tasks and green designating those currently in progress. This dynamic display offers stakeholders an intuitive and up-to-date overview of project progression. In Fig.7(b), the logic of BPMN tasks is revealed through the logical smart contract functions, showcasing how these functions govern the execution of critical project activities.

Meanwhile, Fig.7(c) introduces the access control strategy with strict user authentication via blockchain login accounts. This authentication process ensures varying levels of data visibility across the frontend, catering to the unique needs and privileges of individual users. Furthermore, it plays a pivotal role in safeguarding sensitive smart contract functions, allowing access only to authorized stakeholders. The BIM model is displayed in Fig.7(d) through the BIM viewer, providing stakeholders with a comprehensive visual representation of the project's architectural intricacies. This model is intimately linked to the PeSCL shown in Fig.7(e) , which is used for storing and listing project-specific details. Finally, Fig.7(f) focuses on on-chain data and blockchain-related information, demonstrating the transparent and immutable nature of data stored in the blockchain. Together, these components provide project participants with valuable insights into the structural and organizational dimensions of the project, offering a holistic view of how blockchain-based smart contracts enhance transparency and data integrity in the BIM design collaboration case.

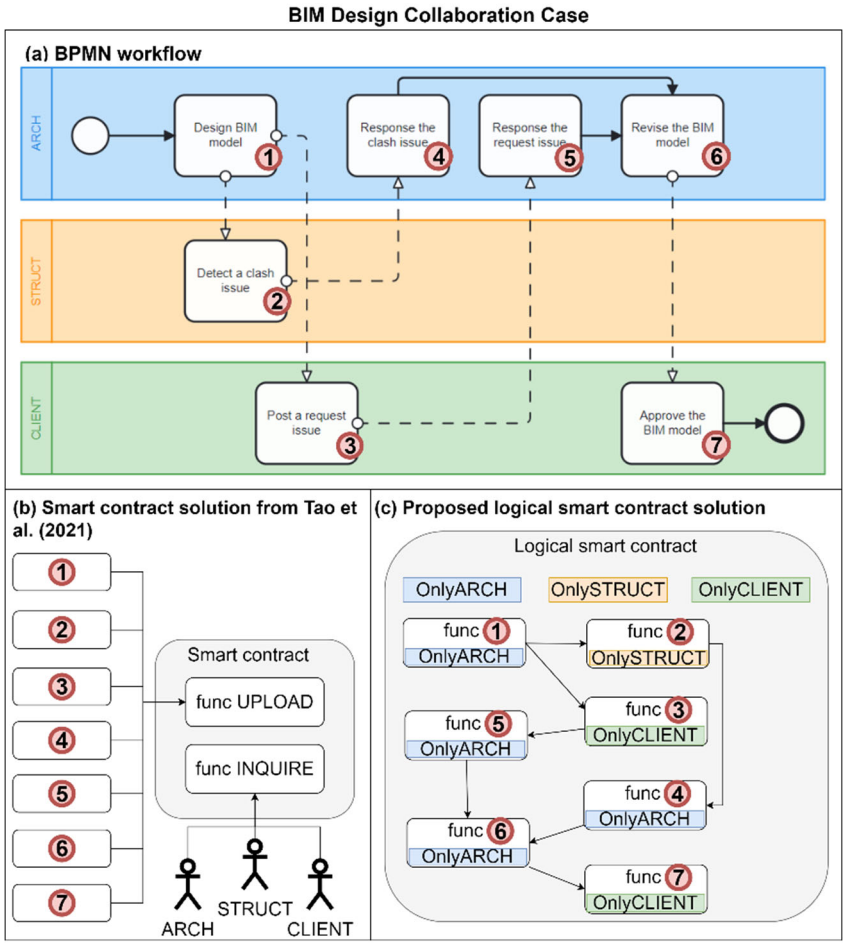

Fig. 6: The comparison of (b) the smart contract from Tao et al. (2021) and (c) the proposed logical smart contract

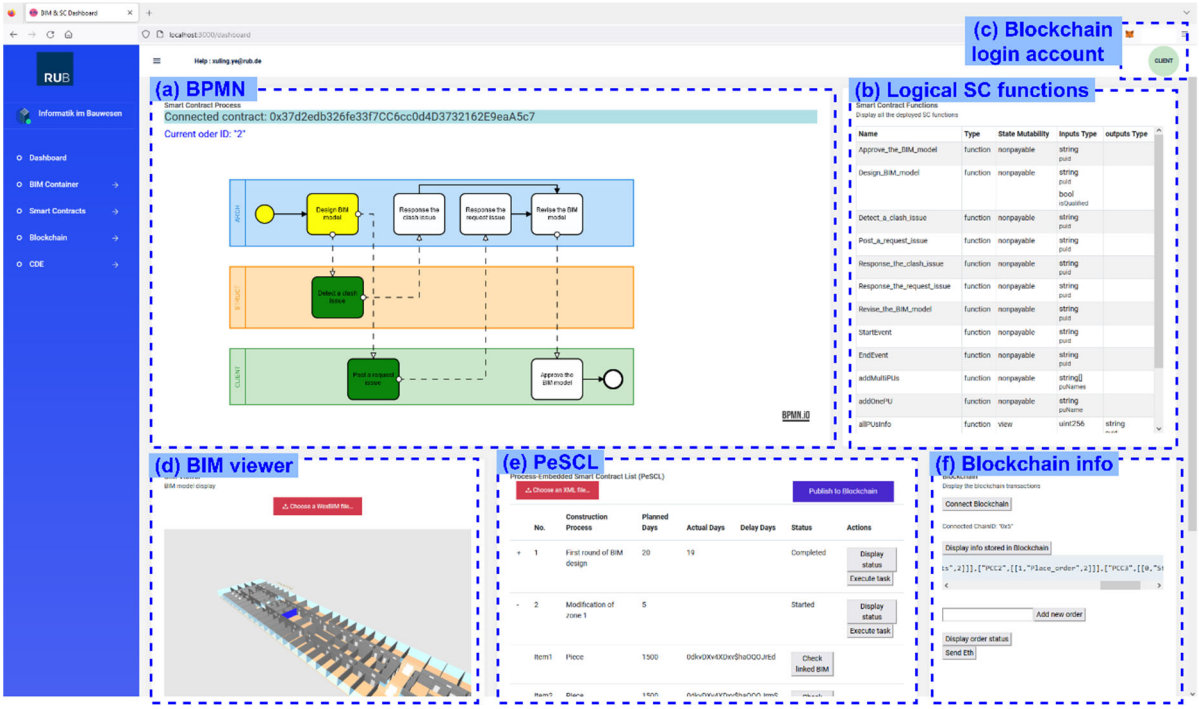

Fig. 7: Results of the BIM design case in the BBI framework

5. CONCLUSION

In summary, the escalating concern for data security in construction business processes has spurred the search for innovative remedies. While the potential of Blockchain and smart contracts is evident, they grapple with substantial drawbacks, notably the isolation of current smart contract implementations and the difficulty non-programming participants face in comprehending smart contract codes within the construction industry. This study has confronted these challenges head-on by pioneering a BPMN-driven approach, seamlessly integrating blockchain and smart contracts while remedying issues related to automation and participant understanding. The introduction of the Blockchain-BPMN integrated (BBI) framework marks a significant advancement, revolutionizing the automation of intricate construction workflows, fostering seamless collaboration, and enhancing visualization across diverse smart contract functions. The strategic inclusion of an access control strategy fortifies data security while preserving transparency. The innovation of logical smart contracts, enhancing automation by embedding task execution flows, is a notable contribution. The feasibility and efficacy of the BBI framework are demonstrated through practical implementation and rigorous testing in a BIM design collaboration scenario. However, a lingering limitation pertains to the immutability of smart contracts. Future endeavors should focus on enriching the framework's adaptability and addressing this issue by incorporating an upgradable feature into the proposed logical smart contracts, paving the way for more refined solutions to the multifaceted challenges inherent in the construction field.

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