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A THEORETICAL FRAMEWORK FOR AUTOMATIC BIM VALIDATION AND SMART CONTRACTS IN THE DESIGN PHASE

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Abstract
The paper provides a theoretical framework that aims at improving BIM validation by automating the verification of information quality and consistency and integrating blockchain-based smart contracts to track the process and shorten the appointment completion. Despite information management using BIM is currently leading the digitalisation in construction, especially in the design phase, misunderstandings about requirements, non-compliant information and late deliveries were detected. For these reasons, the proposed framework integrates innovative technologies and points out their potential impact on automatic information validation, reduction of late deliveries and overdue payments. Though the framework is not yet fully tested, potential outcomes are discussed.

Introduction
As the construction sector is among those with the lowest level of productivity, according to the McKinsey Global Institute, new ways are needed to positively revolutionise its traditional trend (McKinsey & Company, 2020). Digital technologies and advanced automation are shown as factors that, if properly adopted and applied, can optimise the procedures and improve the efficiency of the construction sector (Institute, 2017). In the current digital transformation, the advent of information management using Building Information Modelling (BIM) drives structured and shared information production, delivery, verification, validation and storage through the use of common data environment (CDE) solutions (BSI Standards Publication, 2018a). Despite the expectations, the adoption of BIM has shown complications associated with the management of an extensive digital information flow. Due to a large amount of produced and exchanged information, monitoring and verification became significant time consuming and error-prone. Consequently, some main issues related to the provenance, reliability, accuracy and cybersecurity of exchanged information were detected (European Construction Sector Observatory, 2019a, 2021). Misunderstandings in the information requirements or produced information can cause delays, reworks and unforeseen costs (Nawari and Ravindran, 2019a; Tezel *et al.*, 2019). Expecting to deal with these critical points, the recent literature review related to the construction industry has identified blockchain technology as a stimulating area of research (Hunhevicz and Hall, 2019; Li and Kassem, 2021; Scott *et al.*, 2021). Among the features of the technology, smart contracts have been identified as advantageous tools for boosting and supporting transparent process tracking and automation (Dakhli *et al.*, 2019). The research into these innovative technologies is in line with the positive revolution of the sector. In particular, along with the need to disseminate new digital technologies, the rethinking of design processes represents another fundamental factor for positively influencing the performance of the sector, moving away from the traditional criticalities. Considering these topics, the paper proposes a framework that integrates the automatic BIM validation and blockchain-based smart contracts for shortening the execution of the design phase, assuring the information quality and consistency and securing the reward to the parties involved.

Research methodology
Despite the hurdles, information management using BIM is currently the most suitable solution for structured production, validation and management of information. Thus, blockchain can be a possible response to the issue of information trust and automation in the construction process (Nawari and Ravindran, 2019b; Rodrigues *et al.*, 2018). In this paper, information management using BIM, especially the information verification and validation, and blockchain, especially blockchain-based smart contracts for notarising information and automatically withdrawing payment, are integrated during the design phase for proposing an innovative approach to the traditional and manual verification and validation process.

The paper is organised according to the following sections. The first section justifies the proposed framework by identifying the critical background in which it is contextualised and then highlighting the benefits that can be achieved over traditional approaches. The second section provides the state of the art of both the information validation using BIM and the potential blockchain adoption during the design phase. The third section illustrates the framework of the research, proposing the integration of the automatic BIM validation and smart contracts. Then, since the proposed framework remains at a theoretical level, the main expected outcomes are discussed. Finally, the main value of the research and the future developments are disclosed.

Background and value of the research

The ambition to propose a framework that combines the automatic BIM validation and smart contracts to shorten the execution of the design phase by automating and assuring some procedures is sustained by the analysis of some European and Italian reports. These reports still show major problems which, despite the progressive adoption of BIM, are present. Firstly, late payments and long payment terms represent a challenge for the entire European economy, where the construction sector appears to suffer the most from late payments (European Construction Sector Observatory, 2020). Focusing on Italy, a country-specific analysis reveals that public authorities in the industry tend to have longer than average payment terms, consequently affecting the liquidity of professionals and companies (European Construction Sector Observatory, 2019b). The delays of payments come alongside the second main issue, namely late deliveries. Always in Italy, the "Report on the implementation time of public works" (Agenzia per la Coesione Territoriale, 2018) highlights the long execution periods required to carry out the process. Specifically, the report highlights the incidence of "waiting times", i.e. the time interval between the end of one phase and the beginning of the following, on the total duration of each phase. In the report, the design phase turns out to be specifically affected by long waiting times, which negatively move its total duration.

The background confirms the valuable scope of experimentation of the framework in the design phase. The research question that triggered the development of the framework is: how digital methodologies and disruptive technologies could shorten the validation of the design phase and ensure its proper implementation. The framework provides a theoretical response to the research question by aiming at:

- improving the transparency of communication between client and design team, tracking the process and information exchange;
- ensuring the automatic and exhaustive verification of the quality and consistency of information;
- reducing the delivery time of the appointment, through automatic and effective design validation;
- ensuring incentives to the parties, through the automation of the payment withdrawal and delivery of tokens.

The innovation of the framework lies in the possibility to shorten the design phase execution by automating and notarising the information validation and connecting the approval procedure to payment and tokens release. The framework offers a novel point of view for the adoption of blockchain in the design phase which makes it possible to move away from the traditional approach by minimising validation errors or misunderstandings due to human intervention, limiting the occurrence of disputes through transparent information tracking and incentivising the parties involved with secure rewards and recognition.

State of the art

To support the framework of the research, the key aspects of information validation using BIM, from the definition of information requirements to information validation, are in principle described. Then, a literature review of the current investigations about the adoption of blockchain in the design phase is presented.

Key principles of information validation using BIM

The progressive digital transformation of information management is driving a revolution in the procedures during the overall construction process. In particular, BIM, as an approach based on information management, can be considered the driver of digital transformation (Smith and Tardiff, 2009). This process covers the activities of defining information requirements and the production, delivery, verification and validation of information. Within such a process, each involved participant is responsible for certain information management functions to be fulfilled. According to ISO 19650 (BSI Standards Publication, 2018b), to achieve successful information management using BIM, each involved actor must fulfil three main tasks. The first is the clear definition of information requirements and specifications for their production, validation and delivery. The second is the proper production of the quantity and quality of the required information, and the third is the efficient and effective exchange of information among the involved parties. Each information produced must be verified and validated to double-check the compliance with the information requirements and, consequently, accepted or rejected. In this context, according to ISO 19650, the client becomes the key person in charge of defining the information requirements and verifying the information delivered for each phase of the asset life cycle. Based on the standards, the client both defines the information requirements within specific BIM guidance and plans the verification of the information produced according to the requirements. Continuous monitoring of the progress and compliance with information requirements become therefore fundamental within the digital transformation of the sector. Digitalisation has indeed increased the amount of information to be produced and verified, with the risk that these activities become error-prone and time-consuming. For these reasons, tools for automatic validation have been created to facilitate the control of information within the BIM process (Ciribini *et al.*, 2015). Among these tools, in addition to those for clashes and regulatory verifications, some enable an exhaustive verification and validation of the quality and consistency of the information contained in the BIM models following the client's requirements. The configuration of these tools facilitates and ensures accurate verification and validation of the delivered information.

Despite the efforts to digitalise processes, and BIM standards and guidance promoted by governments, efficient information management is still hampered by the fragmented nature of the industry, the lack of qualified personnel and the difficulty in tracking and maintaining the reliability, quality and intellectual property of information (European Construction Sector Observatory, 2021). For these reasons, alongside the tools for automatic BIM validation, the research proposes the adoption of blockchain technology to ensure reliable tracking of essential information, boost automation of appointment completion and incentivise involved parties in the efficient execution of the appointment.

Literature review of blockchain in the design phase

Among the existing disruptive technologies, blockchain can currently be considered as the main one qualifying the digital transformation currently explored by the most advanced world economies (Tapscott, 2017). Belonging to the Distributed Ledger Technologies (DLTs), blockchain is defined as a trustless technology, that ensures an extraordinary degree of trustworthiness, integrity and immutability (Foschini *et al.*, 2020) and that allows parties to unlock transactions using a distributed peer-to-peer network, without the control of a trusted third party (Baliga *et al.*, 2018; Wust and Gervais, 2018). The level of transparency, accessibility and traceability of shared and stored information using the technology is defined and guaranteed by its architectural design. Among DLTs, blockchain offers unique features, including a considerable number of use cases and the possibility to implement smart contracts and tokens. As previously stated, smart contracts are an important topic of investigation and application in the presented research. Smart contracts, as programs developed on blockchain that execute when predetermined conditions are met, can help in shortening the completion of the appointment. Thanks to their nature, they allow the automated implementation of agreements based on the occurrence and fulfilment of pre-requisites, thus ensuring the outcome for the parties, without the action of a third party and time losses (Ahmadisheykhsarmast and Sonmez, 2020; Das *et al.*, 2020). Tokens are another key feature of blockchain considered in the research. Tokens are digital assets, based on a set of rules encoded in a smart contract, belonging to a specific user and stored securely on the blockchain. They can be fungible, namely, a representation that can be replaced by another identical, or non-fungible (NFT), namely a unique, irreplaceable and non-interchangeable representation of an asset (Lo and Medda, 2020). In the research framework, non-fungible tokens are used to assign a singular digital asset, representing a unique rewarding feature, that can incentivise the performance of the appointed parties.

Although the recent hype around blockchain has focused on the financial sector, the latest explorations of the technology have extended the interest to other sectors, including construction. To justify the integration of blockchain in the proposed framework, the current state of the scientific research on the chosen topic is explored and the existing application proposals are identified, through a literature review. As an innovative technology, blockchain is constantly evolving and consequently, its potential could significantly impact the construction industry (Ablyazov and Petrov, 2019; San *et al.*, 2019), supporting multiple activities across the entire asset life cycle (Hughes, 2017). The literature review carried out supports in-depth research of what has already been studied, highlighting information management using as a relevant area of integration and testing of blockchain (Hunhevicz and Hall, 2019; Jaskula and Papadonikolaki, 2021; Li and Kassem, 2021; Scott *et al.*, 2021; Tezel *et al.*, 2020). According to the existing literature, the production and management of information supported by blockchain could allow the recording of any activity, therefore controlling at any time the real progress of the phase and responsible parties (BSI Standards Publication, 2018b). The integration of blockchain in the BIM process could give confidence and synchronisation to information exchanged, produced, validated and stored. The technology can indeed limit the occurrence of misunderstandings, thanks to its transparency, security and immutability of information. The technology can also guarantee the disbursement of payments and respect of the deliveries, through process automation using smart contracts. Thanks to these benefits, the proposed framework of the research lies among other emerging studies and experimentations related to the integration of information management based on BIM and blockchain in the design phase. Dounas et al. proposed a framework for decentralised architectural design that allows multiple participants to solve the design problems in both collaborative and competitive ways and, through blockchain integration, it can record all the design attempts, including failures, and all the positive steps toward design optimisation (Dounas *et al.*, 2020). Schönhals et al. proposed an approach that makes it possible to protect developed ideas and early concepts even during their systematic development. It intends to protect intellectual property through the digital record of verbal, written or sketched, and even modelled or constructed outcomes during the innovation development in real-time (Schönhals *et al.*, 2018). Another work is from Zheng et al. that proposed an application for mobile devices that allows users to check on their portable devices whether a BIM model is the latest version, whereby, a hash of the BIM model is stored on the blockchain that allows a search service to cross-check the hash of a downloaded model with the hash stored on the chain. After that, the application will provide users with a verification receipt that declares the validity of the model (Zheng *et al.*, 2019). Liu et al. presented a framework that supports the design of sustainable buildings integrating BIM and blockchain. This framework intends to address some potential challenges of BIM for sustainable design such as BIM implementation risk, intellectual property and cybersecurity, level of responsibilities and BIM contract (Liu *et al.*, 2019). Lastly, Singh et al. proposed a framework where the design data generated from design development software are categorised and the data flow is encrypted by using blockchain to track and register the design commands and events in a secure, transparent, and collaborative platform (Singh and Ashuri, 2019).

Framework of the research

The proposed framework explores and shows how the integration between the automatic validation based on BIM and blockchain-based smart contracts could optimise, innovate and shorten the development of the design phase (Figure 1).

To show the main process of the research framework, dynamics of interaction among the parties and use of innovative technologies, here below a step-by-step description of the process is provided. The acting parties are the client, the design team and the information model verifier, and each of them has specific responsibilities and tasks. The client, as the owner or for whom the project is carried out, must conduct all the activities to ensure that accurate information management is satisfied. Therefore, the client defines the project information requirements, protocols for information production, and delivery milestones and sets a common data environment (CDE) solution to support the production, exchange and archiving of models and information among the interested parties. The client has set out the desired information requirements in specific BIM guidance that is transmitted to the design team at the appointment.

Once the appointment has been awarded, the appointed design team develops the BIM models, for one or more awarded project disciplines, containing all the information to meet the client's requirements. In this way, the produced information will respond entirely to the requirements set out by the client, and therefore the design will be realised in a compliant and optimised way. Simultaneously with the development of the information models, the verifier, appointed by the client, similarly receives the BIM guidance.

The verifier undertakes a detailed analysis of the information requirements to translate them from semantic language to machine-readable language through the configuration and adoption of suitable methods. Since the creation and management of a BIM project requires the production of a large amount of digital information, manual verifications are difficult to be performed objectively and exhaustively. For these reasons, to ensure that the information requirements are completely met, the verifier identifies and configures a proper tool that enables the automatic validation of the information content of BIM models according to the client's requirements. Once the production of information is completed, the design team delivers the BIM models, produced for each project discipline, to the client. The delivered models are uniquely stored in the CDE, considered the off-chain database.

The stored files in the CDE are moreover stored and linked with a blockchain network, using a distributed storage system, to keep track of each model delivery cycle. Due to the large size of the models, the distributed storage system creates for each delivered BIM model a cryptographic hash that is stored in the blockchain network through smart contracts. The hash added to the blockchain network enables the inspection of the mapped BIM model that is stored on the computer memory of the peer with the same name as the hash. This makes it possible to control access and changes to the BIM models in a uniform and secure way. When a new model is delivered, its hash and the hash of the already stored models are compared. This makes it possible to check transparently both if the same model has been delivered twice and if the model, claimed to have been revised, has not been modified.

Following the delivery of the BIM models, the verifier uses the configured tool to automatically verify and validate their information content. For each verified model, so for each project discipline, the application independently produces a report containing the verification results. The created reports are stored in the CDE and, likely for the models, their hashes are recorded on the blockchain network hence the progress of the modelling process could be recorded and mapped transparently. In this environment, project verification and validation activities are managed evidently, improving the communication between the client and the design team. The automatic validation of the information speeds up and optimises the review and delivery process. The archiving of the results allows the client to assess compliance with the information requirements. The results of the report reveal the level of compliance of the produced information with the client's requirements, the time when the verification was carried out, the design discipline, the responsible design team, the number of the verification cycle and all the individual errors detected, associated with their IDs.

The level of compliance for which the delivered models are approved is defined by the client in the BIM guidance and communicated to the design team at the time of the appointment. The automatic validation of information included in the models takes place separately for each discipline, so for each model. If the automatic verification of information models produces a report with a result that is below the set level of compliance, the design team receives the report containing all the detected non-conformities and it must proceed with the changes and specified amendments. The design team must then subsequently make a new delivery. If, on the other hand,

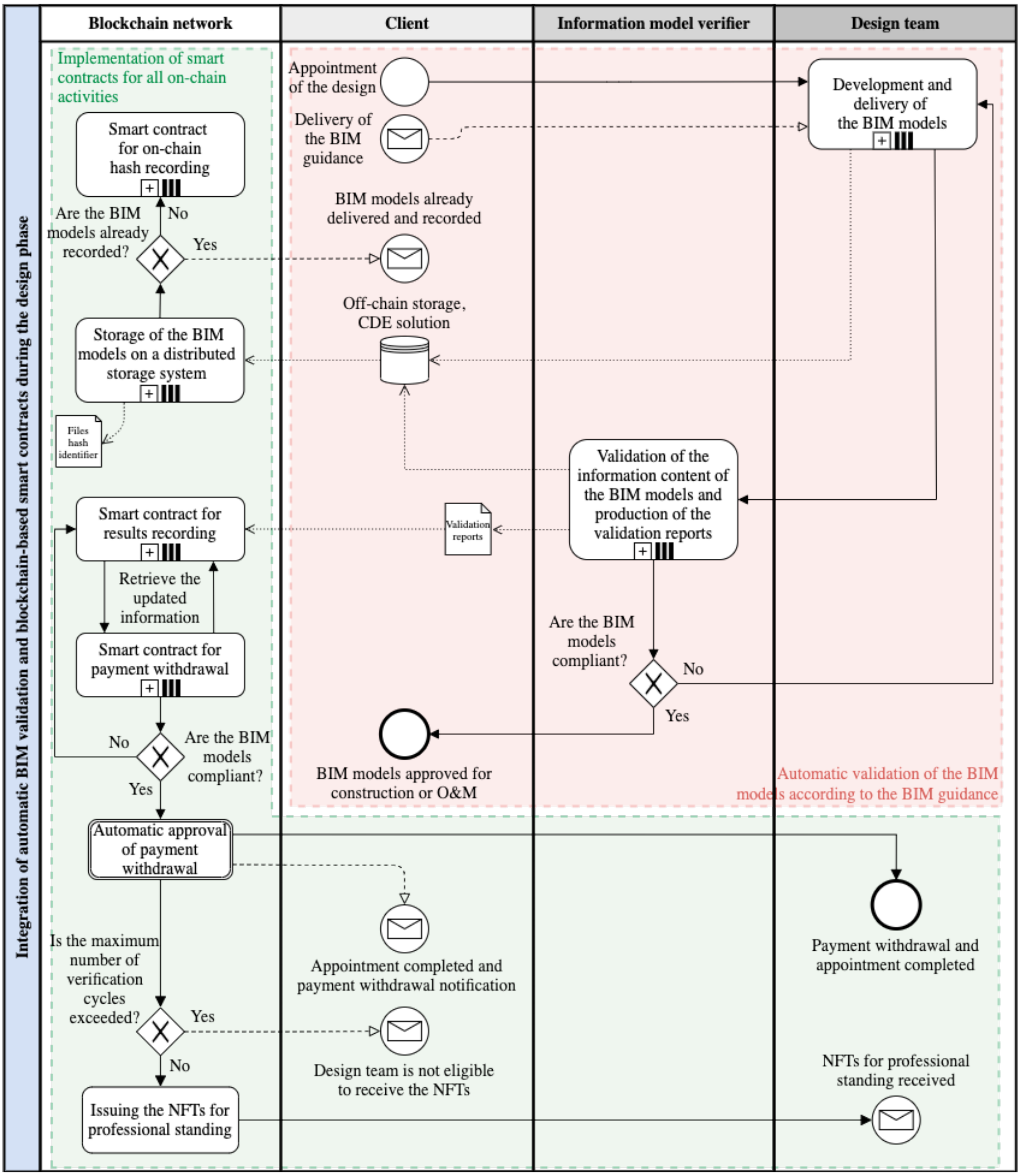

Figure 1: High-level framework of the research

the set level of compliance is met, i.e. information produced has met the client's information requirements, the model is accepted and stored in the CDE, for the future steps toward construction and/or building operation and maintenance.

Once the verification is completed, the results are recorded on an appropriate smart contract that is connected to the smart contract for the payment withdrawal. At the time of the appointment, the client and the design team have established the terms and conditions of payment approval upon its completion. These conditions impose the authorisation for the approval of payment withdrawal when the level of compliance of the delivered model lines up with the set level of compliance. To automate this approval process and link it directly to the results of the model verification, the payment conditions are translated into a smart contract. The smart contract for payment withdrawal is therefore configured to retrieve the information related to the verification results and compare it with the conditions for approving the payment. In the on-chain process, the verification results stored in the first smart contract can be fetched by the smart contract for payment withdrawal that compares whether the level of compliance achieved is equal to or greater than the established level and initiates the transaction. The smart contract for payment withdrawal is linked with an escrow account, that holds and only disburses funds when the appointment is completed as expected, ensuring the payment to the design team.

The pursued business logic makes the coded payment conditions self-execute at the end of each verification cycle of each information model if the level of compliance is equal to or higher than the one set by the client. This process incentives the participants to perform their appointment as stated under the contract. Information produced and included in the BIM models is developed by following the client's requirements and the design team is approved for payment through a smart contract for each completed delivery stage. Therefore, the design cycle, and the subsequent validation, is an iterative process. Information models are only approved when they meet the information requirements of the BIM guidance.

Alongside the automatic approval of payment withdrawal, another incentive system allocated by the client is based on the provision of tokens. These tokens are a digital representation of the performance and skills of the design team, therefore they represent the proof of professionalism and credibility during the appointment of one specific team. For these reasons, the tokens proposed in the framework are non-fungible tokens (NFT), representing unique features earned by a specific team, and they are designed and shared on the blockchain network, thus becoming visible and consultable by all. These tokens are issued only when the BIM models are approved in advance, i.e. with fewer verification cycles than the contractual maximum set by the client. They represent an immutable certification that provides the design teams with good expertise and image for the allocation and award of future appointments.

Discussion of the expected outcomes

The paper illustrates a research framework that combines the automatic validation of the quality and consistency of the information contained in BIM models and the adoption of blockchain-based smart contracts during the design phase. The framework focuses on process automation and optimisation, transferring the activities of information monitoring and validation, as well as those of approving the payment withdrawal, to machine-readable applications, instead of humans. This innovative approach promotes the shortening of the design phase execution, tracks all essential information and ensures the payment. Since the overall research framework is still at its theoretical level, the outcomes discussed are the ones expected by its validation through a proof of concept.

Outcomes of the automatic BIM validation

The practices for producing, reviewing, exchanging and maintaining information recommended by the international standards promote constant interaction among the parties involved. Information management in a BIM environment is characterised by the complete exchange of information whose verifications are dynamically reported and integrated, improving control over the project progress and reducing non-conformities. Due to the high information content of BIM models, it is appropriate to make use of tools that automatically detect errors and non-conformities, facilitating a positive response to the client's information requirements. Therefore, the first main objective of the research will be the setup of an application able to automatically verify and validate the quality and consistency of information according to the client's information requirements and the benefits expected from its implementation and testing are here summarised. Firstly, the setup of the tool could provide the client with an effective application for reviewing carefully the information produced by the design team. The validation of information quality and consistency during the design phase is no longer a manual, time-consuming and error-prone activity, conversely, it becomes comprehensive and detailed. Secondly, the design team would therefore be encouraged to produce information in compliance with the client's information requirements to reduce working time and the likelihood of rework. At the same time, in the event of a negative verification result, obtaining a detailed report containing all the failed elements facilitates the design team in implementing targeted and fast amendments and integrations. Finally, the client can monitor the actual progress of the project and the reliability of the design teams. The detailed verification of the models ensures that the information requirements are met, and the automation of the process considerably reduces the traditional verification and validation time. Indeed, based on some initial observations, it is possible to estimate a reduction in the time required for information validation in the design phase of around 60%. This will be demonstrated through the validation of the research framework on a proof of concept, as further explained in the following section "Conclusions and further developments".

Outcomes of the blockchain-based smart contracts

Regarding the implementation of the blockchain network in the design phase, its architecture requires an appropriate selection and design concerning the involved parties and the project environment. Since the illustrated framework is set in a defined environment driven by a specific client, the second main objective of the research will be the investigation and configuration of the most suitable network. The setup of a blockchain network at the basis of the framework allows the identification of some expected benefits. Firstly, the integration of a blockchain network in the general framework supports the implementation of automated activities. This means that the network could come along and track the information validation in the design phase, eliminating any intermediaries and ensuring the trustworthiness of shared information using consensus protocols and smart contracts. Secondly, the smart contract between the client and the design team would assure the contracting party of the client's willingness to pay and withdrawal of payment upon automatic approval. Thirdly, the awarding of NFTs as recognition of professional expertise and competence provides an incentive for the design team to complete the appointment in compliance with the requirements.

Initially, the permissioned networks will be considered as they allow only selected and known participants to collaborate and transact in the network, ensuring privacy and control of identities. From an architectural and functional point of view, they could offer the appropriate network for the environment of the research framework. In addition, this choice could avoid the problems related to the public visualisation of information and the operating costs due to the fees for using a public network. When the framework will be validated and tested through a proof of concept, it will be possible that other types of blockchain networks will be considered, investigated and tested as well as the possible use of a public blockchain, to maintain the nature and original meaning of the technology. The possible adoption of a public network should consider the organisational, economic and regulatory problems, and also analyse possible alternative solutions capable of minimising the operating costs and latencies, such as sidechains or rollups. The network that responds best in terms of information security, lower latency and lower execution costs for transactions will be the one chosen to configure the desired smart contracts, and it will be adopted during the testing and validation of the framework of the research.

To summarise, the main expected outcomes of the adoption of the framework of the research are related to the (i) optimisation of the BIM validation process, (ii) shortening of the time to complete the appointment, (iii) increased automation of the procedures and (iv) respect of delivery times and assurance of reward.

Conclusions and further developments

The proposed framework illustrates how the adoption of automatic BIM validation and blockchain-based smart contracts could streamline the design phase execution, the information validation and the approval for payment. The combination of the two technologies offers enormous value and could be considered an appropriate direction for the efficient development of the validation activities during the design phase. The potential offered by the framework could fully exploit the information of a BIM-based project. The automation of some processes that are traditionally entrusted to human interactions discloses a crucial area of experimentation. It reduces the human influences on the execution of information validation and approval for payment withdrawal. The validation of the design phase is shortened thanks to the configuration and adoption of a tool for the automatic validation of the quality and consistency of information content of the BIM models. The validation takes place accurately and is notarised on-chain using the appropriate smart contracts, giving transparency and reliability to the process. At the completion of the appointment, the payment approval is guaranteed using smart contracts that execute the transaction upon the compliant BIM validation, when also the release of tokens for professional standing may occur.

The aforementioned outcomes, expected from the adoption and validation of the research framework, will be analysed through the development of a proof of concept. The proof of concept will validate the research framework through the use of a real project based on the digitalisation of the real estate assets of a large Italian public client. This client has developed a proprietary BIM guideline based on which the real estate digitalisation is appointed. In this project, the sets of rules for automatic validation in compliance with the contents of the proprietary BIM guideline will be created and tested, as well as smart contracts for notarisation of files and information and for approval of payment and tokens release. Through the implementation of the proof of concept, future publications will validate the expected outcomes as well as discuss the main benefits and limitations.

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