Upkeeping digital assets during construction using blockchain technology

Marijana Srećković, marijana.sreckovic@tuwien.ac.at
Institute of Interdisciplinary Construction Process Management, TU Wien, Austria
Goran Šibenik, goran.sibenik@tuwien.ac.at
Institute of Interdisciplinary Construction Process Management, TU Wien, Austria
Katharina Sigalov, katharina.sigalov@rub.de
Department of Civil and Environmental Engineering, Ruhr-University Bochum, Germany
Xuling Ye, xuling.ye@rub.de
Department of Civil and Environmental Engineering, Ruhr-University Bochum, Germany
Markus König, koenig@inf.bi.rub.de
Department of Civil and Environmental Engineering, Ruhr-University Bochum, Germany
Katharina Reitmayer, k.reitmayer@freundlieb.de
FREUNDLIEB Bauunternehmung GmbH & Co. KG, Germany

Abstract
This paper presents two frameworks for the application of blockchain technology with Building Information Modeling in the design and construction phase, and further explores their coupling for the management of digital assets with a use case demonstration. The research shows that the implementation of blockchain and smart contracts is context dependent and differs according to process requirements. In the BIMd.sign framework, smart contracts enable a transparent and traceable design workflow, whereas in the BIMcontracts framework, smart contracts enable transparent and automatic payments during construction. The coupling of frameworks requires predefined and identical standards for information management. The use case shows: the exchange of information needs to be coordinated according to the contractual agreement; digital assets need to be set up in such a way to allow for a flawless exchange of information; and blockchain and smart contracts facilitate transparent, traceable and automatized processes in regard to digital asset management.

Keywords: design, construction, asset management, BIM, smart contracts

1 Introduction

Several theoretical or conceptual applications of blockchain (BC) technology in the architecture, engineering and construction (AEC) industry in combination with Building Information Modeling (BIM), are already proposed in literature (Erri Pradeep et al 2019; Nawari & Ravindran 2019; Hunhevicz & Hall 2020). It has been shown that the AEC industry could benefit from the implementation of BC and smart contracts (SC) to significantly increase transparency, traceability, and automation of the design and construction processes in the lifecycle of a building project (Li et al 2019; Perera et al 2020). The different value chain activities, actors and digital assets could be linked on the basis of BC and SC. Currently, only independent solutions or approaches are available, with very few empirical demonstrations in AEC. However, these new technologies have the potential to improve integrated design and construction processes.

With the objective of exploring possible applications of BC and SC in AEC in practice, this paper aims at addressing the following research questions: How can changes occurring during the construction phase of a building project be managed/kept up with, using BIM, BC and SC?

What are the requirements for that BC-supported processes? For that purpose, first, we introduce the conceptual frameworks for the application of BC and SC in the design and construction phases, followed by a use-case demonstration of the framework coupling for the support of change management during the construction phase. Finally, we discuss the use case and end with the conclusion and research contribution.

2 Literature Review

2.1 Digital assets and BC in design and construction

In the design and construction phase, there is continuous transformation of information from digital assets (model, data, documents) into physical assets and vice versa (Succar & Poirer 2020). The management of these assets is a necessary process for the delivery of the contractually agreed services and deliverables, i.e. model (e.g. BIM), turnkey construction, which also includes upkeeping changes and amendments occurring during design and construction workflows in practice. Building Information Modeling (BIM) enables information from all project phases to be stored in a single digital model (Love et al 2015).

BC technology provides interesting properties for a potential support of these workflows. In connection with BIM, the potential of BC lies in the so-called record of changes, where traceability of modifications and updates to the BIM-Model could help the standardization of BIM processes (Mason & Escott 2018), and make design workflows more transparent and in parts even automated through the implementation of SC. Connecting the BIM-Model with completed construction elements on the construction site as well as automatic payments, offers a possibility for implementation in the construction phase (Nawari & Ravindran 2019). Automatic payments, tendering and awarding could also be achieved via a transaction-based database (Wang et al 2017).

The immutability of data after it has been added to the ledger (Abrishami & Eleghaish 2019; Nawari & Ravindran 2019), is rounded off by the property of BC that data can only be added and no longer removed, which allows for a permanent chronological list of events on the BC (e.g. documentation of BIM-Model updates). This results in a potentially precise traceability of digital assets (model, change orders, lists, bill of quantities) and their modifications as well as transparency of activities (transactions, payment, procurement) of different actors in a design or construction workflow. Exact time stamps and information about the authors of the added data could thus resolve points of conflict (Turk & Klink 2017) and would potentially serve as a reference for e.g. warranty or claim management. As a secure infrastructure for data exchange, BC offers increased transparency in collaboration through decentralized organization (Shojaei 2019). Trust, as another feature of BC - achieved primarily through so-called consensus mechanisms between participating actors, enables autonomous verification of transactions as well as equality of all copies in the network, which also serves as a basis for decentralization (Nawari & Ravindran 2019) where intermediaries are obsolete.

2.2 Information management and exchange

The increasing use of BIM as a working method has enhanced the need for close and coordinated collaboration and information management. This has facilitated the development and widespread use of common data environments (CDE). The CDE is a combination of technical solutions underpinned by workflows (NBS 2020) and provides functionalities, like workflow support and secure data management. For larger construction projects, the use of a CDE as a single source of information is indispensable and highly recommended by the ISO guidance (ISO 19650-2). The most important function of a CDE is the management and versioning of information containers. An information container can be any structured (e.g. geometrical models, XML files, bill of quantities (BoQ)) or unstructured data set (e.g. documents, photos). All authorized participants, under the definition of specific individual access rights, can use these data sets. The growing need for uniform data exchange of cross-domain models (e.g. 4D or 5D BIM) as one information delivery, resulted in the development of the ISO-standardized Information Container for linked

Document Delivery (ICDD) for standardized data exchange of linked data sources, using a generic information container format (ISO 21597-1).

A CDE is a well-suited and secure data storage for digital assets in construction projects. Storing a large amount of data on a public BC is very expensive and not efficient, otherwise private BC are critical in terms of security and trust. Hence, it is proposed to keep all the sensitive and important information in a centralized off-chain storage. Thus, only unique cryptographic hashes of the files deposited in the CDE can be recorded on the BC.

Detailed user-defined specifications of the information that need to be exchanged at particular points within a BIM project can be defined as recommended by the ISO-standardized Information Delivery Manual (IDM, ISO 2016). buildingSmart (2021) recognizes that the development of IDMs is difficult for some domains, and that it should be accompanied by software development (Sibenik and Kovacic 2020). Although the format for information exchange is standardized, predefined workflows are not a promising solution in a heterogeneous AEC industry, since projects are created by loosely coupled project-specific organizations. Different constellations of project participants influence the workflows, which cannot be foreseen in a predefined workflow description, especially in the design phase where e.g. domain-specific planners are exchanging digital assets in numerous iteration loops and different modelling tools. Therefore, the workflows need to be defined and supported in real time, which is why the creation of SCs on the go - depending on the project specific workflow and digital/physical assets - could offer a suitable solution.

3 Overall Frameworks

In this paper, two existing frameworks for the application of BC in the AEC domain using BIM are presented and coupled, enabling herewith a continuous information exchange and documentation (Fig. 1). The BIMd.sign framework focuses on the design phase and the use of BC and SC for traceable documentation of the delivery and approval of BIM models. Thus, important activities and decisions during the design phase are documented transparently. Based on the created BIM models, the BIMcontracts framework partially digitizes a construction contract and enables automatic payment after verification. Again, individual interactions between client and contractor are documented transparently and comprehensibly using BC.

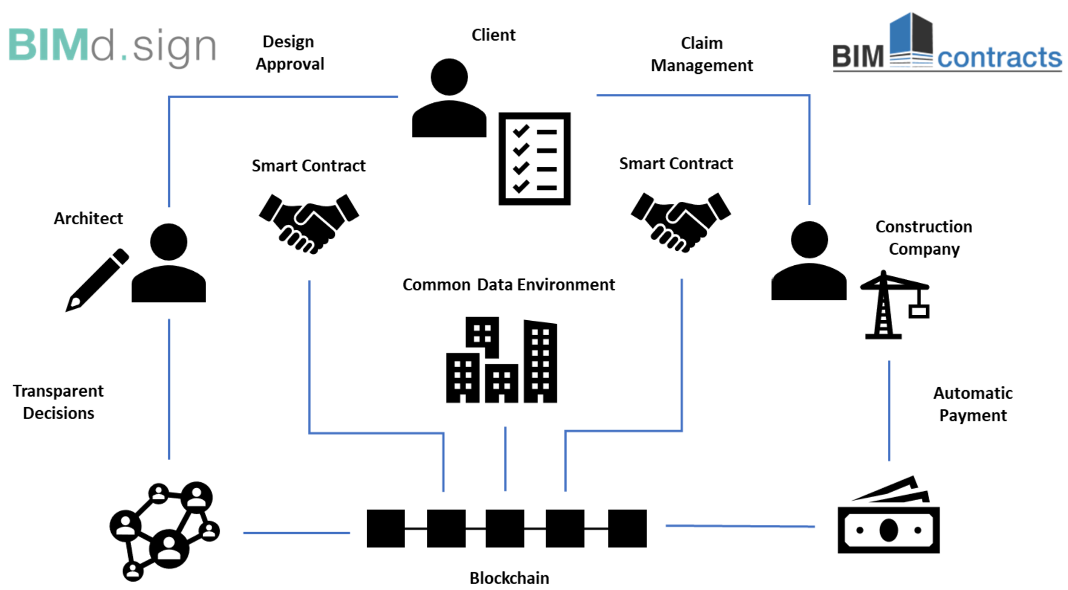

Figure 1. Framework BIMd.sign & BIMcontracts

The two frameworks use identical standards, so that a coupling of both concepts is possible. The BIMd.sign and BIMcontracts systems employ the private consortium blockchain GoQuorum. This Ethereum-based blockchain implementation improves scalability and performance. In both concepts smart contracts are considered as a service solution. The cost for the conclusion and the execution of the contract may be shared by clients and the relevant contracting party, as both parties benefit from this service.

In the first step, the individual frameworks are briefly introduced. Subsequently, the coupling of both frameworks is presented with a use case demonstration.

3.1 BIMd.sign Framework

In order to capture processes, it is necessary, first to understand how they are designed, second how they need to be configured for BIM, BC and SC and third, how to continuously adjust the fit between digital technologies and business processes or workflows (Srećković et al 2020). In Figure 2 the configuration of an exemplary workflow in the design phase, including information processing of digital assets (data-flow) and coordination of activities (process flow) between different actors (client, domain-specific planners) is presented. It reflects the exchange during a design activity and shows the complexity resp. interrelatedness in the information processing of different digital assets. Each step in the process flow has actors responsible for their own domain-specific tasks and fulfillment.

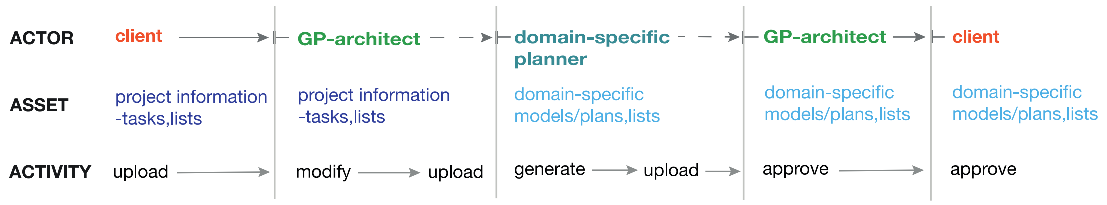

Figure 2. Actor/Asset/Activity Workflow

In the BIMd.sign framework, the role of BC and SC in the design phase is to trace the activities performed on the specific digital assets (e.g. BIM-Model, plans) during the whole phase and allow these activities to be transparent for the relevant participating actors. Hence, SCs could facilitate the traceability of relevant modification in the digital model, where the author and date of a change would be documented on the BC. Furthermore, process steps, which are executed in iterative loops (such as the repeated exchange of digital assets between different domain-specific planners), could be automatized with SC, generating a more efficient workflow.

The conceptual framework (Fig. 3) starts with the commissioning of the design services according to contract by the client. This paper-based contract is stored on the CDE. The services of the General Planner (GP)- based on the procurement model in Austria resp. Germany (LM.VM 2014; HOAI 2013) - usually assumed by a superordinate architecture firm, include the complete design package and often further management services in the project if so contractually agreed. The project requirements are defined by the client and are the basis for the execution of the project and the assessment of all activities addressing function, form, budget and time (Cavka et al 2017), as well as the evaluation of the delivered digital and physical assets. At the end of each process or stage in the design phase, the GP presents the results to the client, who either accepts to move forward or requires changes, which end in iteration until the design is approved. According to the procurement model, the GP is coordinating and organizing all design services and acting as the intermediary between the client and the domain-specific planners. The architect (domain-specific planner) develops e.g. the conceptual design and uploads it to the CDE. The structural engineer (domain-specific planner) is responsible to check if the uploaded model fulfills all the domain-specific requirements. If not approved, a list of required changes is uploaded for the architect, who modifies the design and uploads the updated model for the structural engineer to the CDE. If approved by the structural engineer, the architect then authorizes further steps. In this case, the SC would be able to document the changes and responsibilities of the involved actors, as well as give clearance for further steps, when all approvals are met, completing this SC and possibly triggering a new one. Hence, each of these steps is supported with a SC, which also partly automatically defines the possible next steps. The actors are also able to define the next steps by choosing a SC, which is regarded as another digital asset during the design phase.

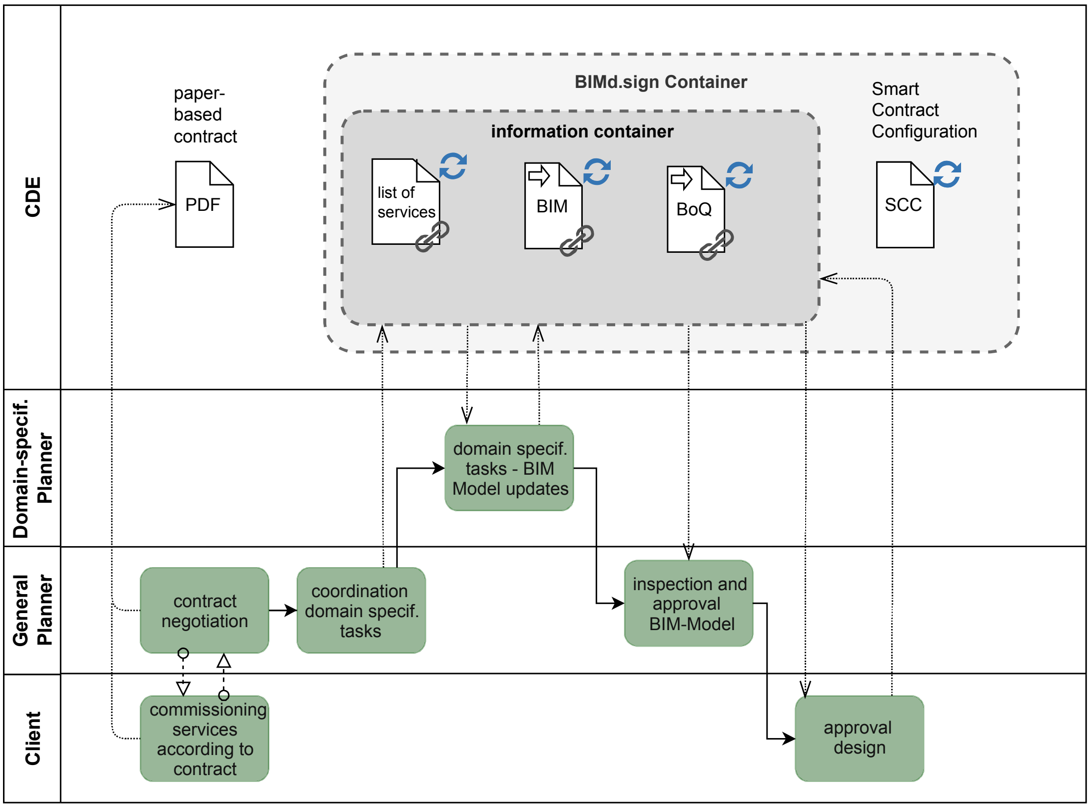

Figure 3. BIMd.sign concept

In the BIMd.sign framework any new version of digital assets could reference the previous one, which creates a transparent design workflow progress. Hence, based on the data stored on the BC, the SC enables the tracing of the workflow progress' status and automatically (according to code) permits further processing of data if the specified requirements, defined within a SC, are fulfilled.

3.2 BIMcontracts Framework

The BIMcontracts framework investigates automated payment between clients and contractors. The framework proposes the solution for contract management applying blockchain-based smart contracts combined with BIM. The parties still conclude a conventional construction contract and only parts of it are transferred into a smart contract. Once the tendering procedure has been carried out, it is possible to start with a conclusion of a formal contract. The client or the contractor should provide agreed-upon digital BIM-based tender documents: a digital building model (BIM-Model) linked with materials, works, and their cost in the form of a detailed Bill of Quantities (BoQ), best with Quantity Take-Off (QTO). This linked information, representing a part of a 5D BIM-Model, can be provided as an information container. For the automation of payment-related transactions via smart contracts, a billing plan has been developed and proposed in Ye et al (2020). The billing plan comprises billing units, containing inputs about lump sum or unit price with quantities and referencing the construction work items and building elements to be completed by linking to both the BoQ and the BIM-Model. Billing units should be determined in advance by the parties during the contract negotiations and can be formed at a different level of detail. The linked BIM-Model, BoQ, and billing plan can be also combined into a single information container referred to as a billing container (Fig. 4).

Based on the agreed and loaded billing container, the so-called Smart Contract Configuration (SCC) is used to customize and generate a specific smart contract based on pre-defined templates. SCC is a machine-readable representation of all relevant information and agreed-on contract terms. It consists of data about the contractual parties, digital assets, and the customized execution details referred to as billing arrangements. After agreement on the terms and conditions has been reached, all relevant information is stored in the CDE using ICDD-standard. This so-called BIMcontracts Container (BCC) is an extension of the billing container with the SCC (Fig. 4). The calculated hash values of both container and internal files (BIM-Model, BoQ, billing plan, and SCC) are included in the confirmed paper-based contract to identify the contractual billing basis. After the signing of the paper-based contact in the next step, a PDF of it and its hash value are also loaded into the BIMcontracts system and stored in the CDE. The SC is generated and sent to the blockchain as soon as both contracting parties sign it with their BC identities, whereby the execution can start.

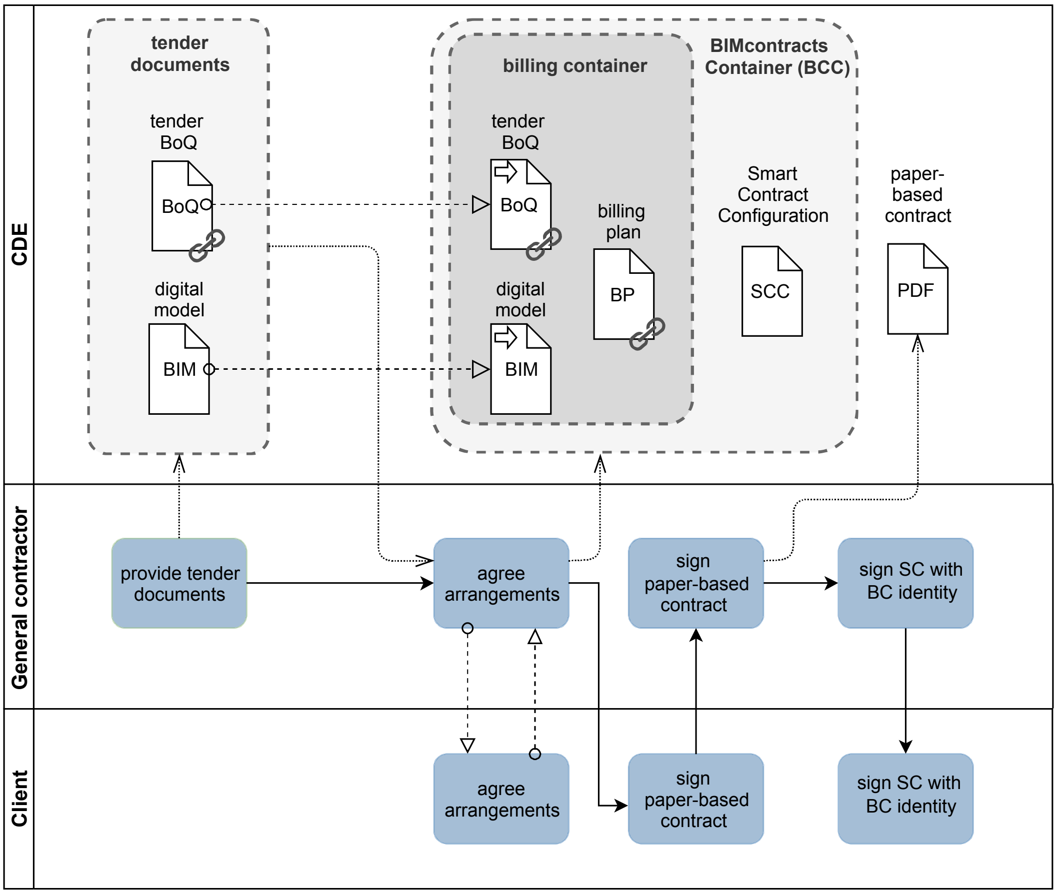

Figure 4. BIMcontracts concept

During the execution, the work performed as well as the occurring construction problems are documented by the contractor. Once the contractually agreed construction works have been checked and accepted by the client, checking results are stored in the CDE. In response to the confirmation of the client, the SC triggers an automated bank payment based on the billing plan data and the SC conditions.

4 Use Case

4.1 Project overview

For demonstration, we are introducing a use case scenario of a three-story office building during its construction phase, situated in Dortmund, Germany. In our presented coupled framework, the exchange of the digital assets (BIM-Model with linked BoQ) serves as the interface between the GP-Architect and the GC-Construction company, using a CDE. In this scenario, a required change in building design made by the client, such as the removal of windows on the northern façade during construction, triggers a change management process. This occurrence includes several actors (general planner, domain-specific planner, general contractor, subcontractors), activities (updating a digital model, procuring, paying) and digital assets (BIM-Model, building permit, bill of quantities).

4.2 Organization

Depending on the legal framework conditions (awarded contract) and the procurement model, the general planner (GP) and the general contractor (GC) have different responsibilities and obligations (Fig. 5).

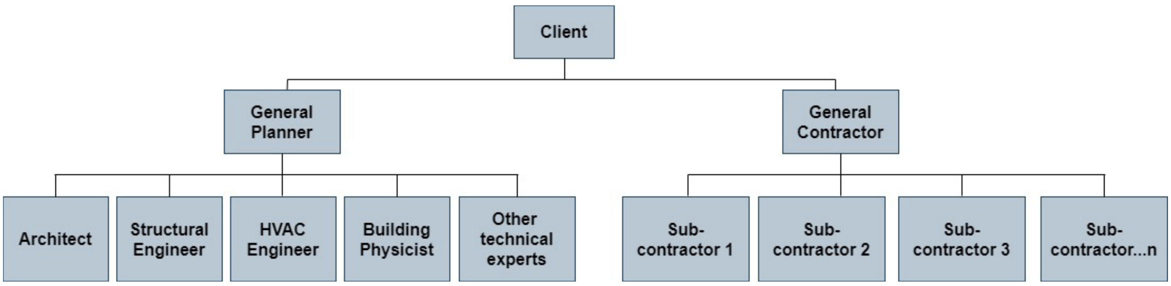

Figure 5. Project organization according to the procurement model

The GP signs the contracts with the client and is the lead consultant in the design phase. He appoints all the domain-specific planners, in disciplines i.e. architecture, structural engineering, HVAC engineering, building physics. He assumes the responsibility and liability for the individual design services and provides the client with a guarantee that these services, including all interfaces (digital assets) between disciplines are correct The GP owes the client the BIM-Model (as planned) and the BIM-based tender documents i.e. BoQ with QTO.

In the use case scenario, the GP is responsible for the creation of the functional specification and tender preparation, offer evaluations and award negotiations. If the award has already been determined in the course of the design phase and an assignment is to be made to a general contractor (GC), the tender is usually functionally structured and follows a trade-specific structure or DIN 276 (2018). In the case of individual awards or in the contractual relationship between the GC and its subcontractors, the tender by trade with specification of services is common. In accordance with the procurement model, the services of the GP include in our scenario the complete design and management package. Hence, the GP takes over the services of cost control, site supervision and documentation during the construction phase and is therefore involved in the project phases 1 - 8 according to the plans of work and services (HOAI 2013; LM.VM 2014). In addition, the GP assumes responsibility for updating the model (as-built BIM) during construction.

The GC signs a contract with the client and is responsible for delivering the turnkey construction. After conclusion of the contract, the BIMcontracts Container is stored in the CDE and SC is deployed on the blockchain. As the work proceeds, unforeseen factors could lead to the need for change. Thus, some work will have to be added or to be removed from the original scope of work agreed in the contract. There may be global changes that affect the individual technical digital models, such as adding or removing of elements or editing of the element properties. Such modifications can lead to further adjustments in other technical models and imply an update of the BoQ and the billing plan. Besides, the BoQ can also be changed without the BIM-Model being affected. Omission of services, changes to services (e.g. additional quantities) or any additional services (without BIM planning) are possible und should be considered in the billing plan. In addition, the adjustment of the billing plan independently of the other parts may also be necessary, in the event of restructuring or splitting of billing units. Furthermore, a subsequent amendment of the Smart Contract Configuration (e.g. configuration of payment arrangements) is also provided.

4.3 Workflow

In our presented scenario (Fig. 6), the client's change order – the request of omission of windows on the northern façade, triggers a change management process in the construction phase.

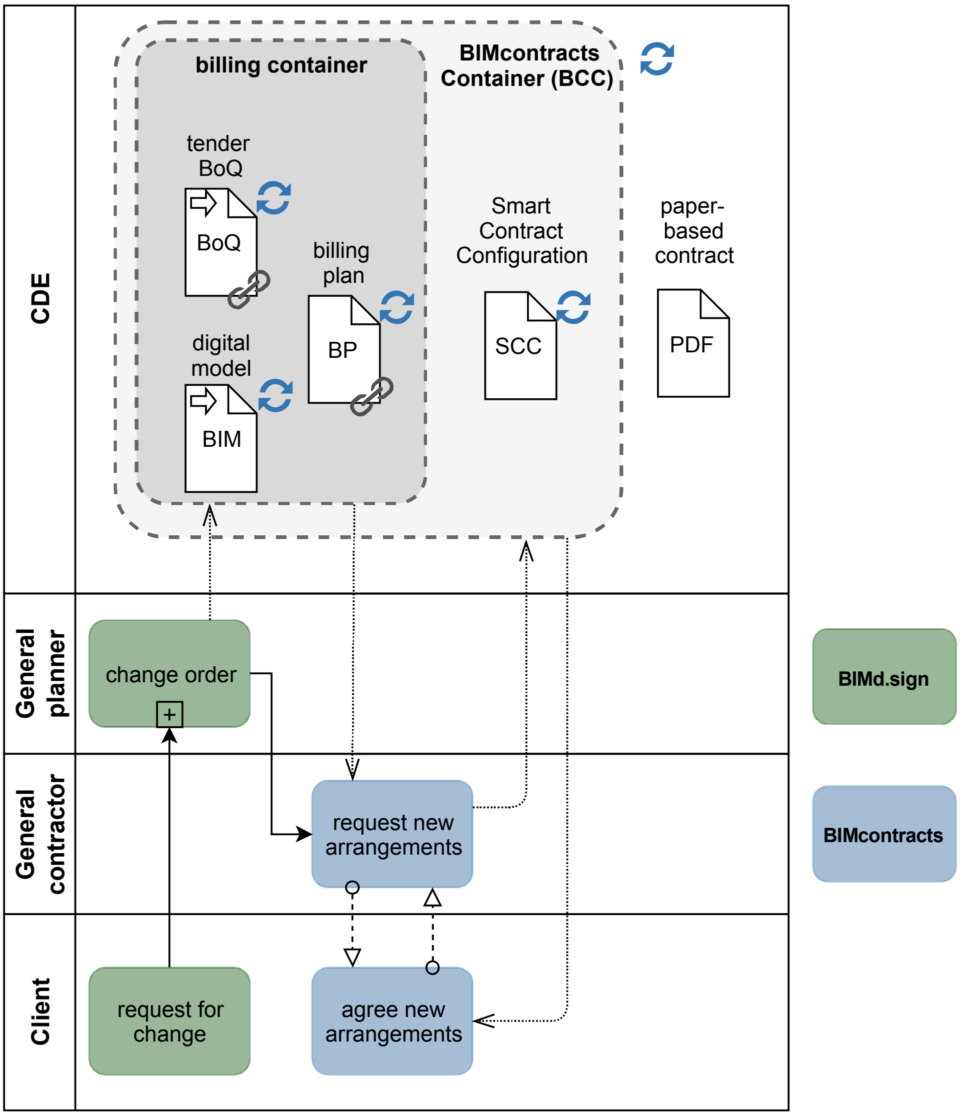

Figure 6: Change order management BIMd.sign/BIMcontracts

The client communicates the change request to the GP, who coordinates these changes with his domain-specific planners. The GP inspects and approves the modifications to the BIM-Model and generates the change order with an updated description of services/BoQ, which is forwarded to the GC. Once the GC calculates and completes the change order, the GP inspects and sends the change order for approval to the client. The client receives the documents to carry out a final check and to approve the change. For the realization of the change order, the client must submit a change in design to the approving authority in order to receive a supplementary building permit. Otherwise, the change in design (omission of windows) would prevent the acceptance of the turnkey construction respectively the issuance of an exploitation permit. The outlined change should be made before the shell is accepted. Any other notification of deficiencies relating to the completion of the shell is to be released respectively corrected by setting a deadline for the submission of the change order. After all the approvals (by the client and the approving authority), the GC executes the aforementioned amended construction services.

All these changes affect one or several digital assets from the BCC and result in a new version of assets and of the container stored in the CDE. The new hash values of the container and the internal files are calculated and saved within the new SC. Since these changes are an amendment of the original contract, active consent of both contracting parties through the signing of a new smart contract via their uniquely identifiable BC identities is required.

5 Discussion and Conclusion

With the presented BIMd.sign/BIMcontracts framework we aimed at answering two research questions: *How can changes occurring during the construction phase of a building project be managed/kept up with, using BIM, BC and SC*? and *What are the requirements for that BC-supported processes*? In response to the research questions and with the objective to show how the frameworks can improve reliability and efficiency compared to traditional workflows in design and construction, the findings can be summarized as follows:

- *Phase-dependent context*: The coupling of the two frameworks shows that the implementation of BC and SC is context dependent and differs according to process requirements in the design and construction phase. In the BIMd.sign framework, BC and SCs enable a transparent and traceable design workflow or parts of it, whereas in BIMcontracts, BC and SCs enable transparent and automatic payments in the construction phase.
- *Diverse data structures*: In practice, the used digital technologies (e.g. BIM) have different interfaces and different data structures belonging to various actors and activities, which means that a flawless exchange of digital assets (model, data etc.) is a necessary requirement for the integration of design and construction workflows. This still poses a problem, due to numerous software interoperability issues and different data formats used by various disciplines participating in a project, among other things. The analysis of the use case shows, for the use of BC and SC, the digital assets (e.g. BIM-Model) of the design phase should already be set up in such a way to be easily and automatically incorporated into the tendering and billing models for construction work. To ensure a proper information exchange, the presented approach uses the ISO-standardized Information container for linked document delivery (ICDD) for cross-domain linked models (BIM-Models enhanced with costs and payment-relevant data).
- *Documentation and Transparency*: SC enable automatized reference-making on a BC and therefore create a revision-safe database. With a BIM element-based system, SCs facilitate the traceability of each change in the design-phase model. Author and date of a change can be tracked on the BC. In particular, transparent and clear documentation and coordination of the various trades based on BC would be useful for efficient execution and simple billing in the construction phase. The documented provision of services including possible defects or reworking is again important and has to be synchronized with the design-phase digital model. Furthermore, changes in other digital assets, such as the bill of quantities, also have to be stored consistently and be traceable. This traceability enforces a responsible decision-making process and can help avoid legal disputes upfront, as well as minimize the restraint of using BIM in an inter-organizational setting.
- *Workflow reconfiguration*: Another important issue is that processes in design and construction need to be reconfigured and adapted for digital technologies, such as

BIM, BC and SC, which requires the rethinking of existing traditional workflows. The realization of the proposed frameworks therefore requires digitally-adapt processes in practice.

The contribution of the presented research is threefold: First, we show potential implementations of BC and SC in the design and construction phase with our conceptual frameworks; second, we demonstrate a framework coupling using a change order and its implications on the contractually agreed design and construction services; and third, we propose how in that case, the upkeeping of digital assets would be supported with BC and SC. The use case shows (1) that the exchange of information needs to be coordinated between the actors (GP, domain-specific planners, GC, subcontractors) according to the contractual agreement and procurement model, (2) digital assets need to be set up in such a way to allow for a flawless exchange of information from design to construction, and (3) that BC and SC facilitate transparent, traceable and automatized processes in regard to digital asset management. The limitations of our research are that the proposed implementations of BC and SC in design and construction still need to be assessed in practice. The development of prototypes is currently underway and will be tested in a further step in the BIMd.sign and BIMcontracts projects.

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