Blockchain-supported design tool on building element scale

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Abstract

Sharing building data or building models still represents a problem within design practices in the architecture, engineering and construction industry. Additionally, digitalization, automation or traceability of processes face numerous workflows and changing stakeholder constellations, with multiple software tools escaping the scopes of common data environments or similar digital solutions. Vague standardization regarding data and processes hinders data management technologies from overcoming the design phase digitalization issues. While many central solutions still deal with closed data due to many proprietary tools for domain-specific tasks, each building project requires an inter-domain collaboration. Open solutions to holistically manage projects still lack functionality, even though some existing tools support central data management and process automation. This research investigates data management using popular data exchange formats for coupling with blockchain technology. It establishes a system that can support processes with smart contracts and reference building elements, herewith addressing the question: How to manage data on the building element scale to allow for processes defined with smart contracts and blockchain technology? The resulting system architecture combines Revit as user-local storage and Speckle as an open CDE. Furthermore, it uses the Baseline Protocol for data exchange and as a common point of reference. While data exchange happens off-chain, cryptographic hashes of data are stored on the blockchain to form a single point of reference for process states and all previous versions, creating process chains and allowing data traceability. Data tracing is an essential requirement for building projects, still commonly realized in analog form in practice. This research presents mechanisms for blockchain-based data tracing on a level of granularity required for design processes.

Keywords –

Blockchain; Baseline; CDE; BIM; design workflow

1 Introduction

The building design process is characterized by numerous stakeholders contributing to the design of a single real-world product. However, such a single real-world product is not reflected on a single data repository due to several reasons: models differ between domains, domain-specific models are proprietary, the data exchange process is burdened with difficulties, data ownership is not regulated, existing platforms exclude some stakeholders or software tools, to mention a few. Although ISO standard 19650 [1] suggests using a common data environment (CDE) for the building design process, it does not specify how it should be used and hence differs between projects across the AEC industry. The realization of CDE products is not standardized, and the products provide various functions and solutions [2]. Besides all the problems existing in the data management of a building project, blockchain (BC) is evermore present in all the phases of the building life cycle [3]. The visionary advantages of distributed ledger technologies might be suitable for resolving the AEC industry's communication issues [4]. Therefore, we aim to improve the design process with BC technology. The BC concept for the design phase that we propose allows for better transparency, traceability and data reliability. It can improve the communication between stakeholders with limited trust and individual data management systems (DMS). Building data as the main product of the design phase and additional necessary information must be adequately integrated with the BC concept and further made available in a form suitable for generating added value facilitated by the new technology. However, data required for this purpose has not yet been structured to relate it to BC; even for integrated planning, it has not been organized in a suitable way and on a sufficient level of granularity. Therefore, this paper aims to investigate the organization of information and documents and its appropriateness for the design process with BC. The BC-supported design phase framework needs a critical survey of DMSs.

DMSs considered in this research are:

- a communication platform using documents represented as data files
- a server using IFC standard, which manages data on an object scale
- an existing CDE solution and corresponding data management
- a previously developed solution for data exchange between architectural design and structural analysis using a database MongoDB for storage

These DMSs will be the center of the investigation. We focus on the usefulness and usability of their data organization strategies regarding their integration with a BC solution realized through the Baseline Protocol in the building design process. The following section reviews the existing literature regarding the BIM-based design process, DMSs and versioning, and already recognized relations to BC technology. The methodology used to test the data management solutions is presented in Section 3; findings are presented in Section 4 and the system prototype demonstrated in Section 5.

2 Literature review

The literature review briefly addresses three topics that are relevant for this research:

- Design processes – described as analog, workflows are heterogeneous and in practice rarely automated
- DMSs and versioning – isolated solutions provided for specific practices, where proposed solutions do not form a technological ecosystem for inclusion of all domains
- BC – popular in recent years, has not yet reached a useful solution for broader use, problems and benefits in the construction sector need further exploration.

2.1 BIM-based Design Process

BIM is considered to be a "use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions" [1]. A built asset is of interest to many stakeholders throughout all stages of its lifecycle. These stakeholders often have different interests and accordingly use domain-specific representations of an asset. They may not even use building models which involve building geometry and may solely use alpha-numeric data [2]. Three ways of achieving model-based collaboration are recognized [6]: through separate BIM models, through separate BIM models with an aggregated model, and a single BIM model.

Apart from these technology-related issues, BIM contractual arrangements concerning collaboration among stakeholders need to be taken into consideration [7]. A high-level design process structuring [8], [9] serves well for establishing contractual relations between the stakeholders, but mostly between hierarchically separated actors. Stakeholders constitute a loosely-coupled system in the most common case [10], [11] where multiple companies cooperate on a single project, based on contractual models arranging their relations. Nevertheless, communication between domain-specific planners is not contractually regulated [12], and results in numerous workflows across the industry. Patterns can be recognized between these activities [13], supporting possibilities for standardization. Attempts to standardize a BIM-based design process originating from the project management domain are based on traditional workflows and do not result in an automatable standard (e.g., [14]). Processes for cost estimation can be investigated through logs [15], which is software-specific and does not show the processes which stand in relation with other stakeholders (communication processes). Such processes are generally underinvestigated, present a research gap [16] and a requirement for workflow automation. Design workflows, and herein communication processes have the potential to be supported through Smart Contracts – i.e. decentralized computer protocols that autonomously, self-execute predefined tasks [17], fostering simplified, interdisciplinary processing of design tasks [18].

The research stemming from the project BIMd.sign [19] describes three scenarios in the design phase for the use realization of smart contracts. Such scenarios will represent the point of departure for this research due to the lack of documented and standardized communication processes between the stakeholders, and the scenarios will be more closely explained in the methodology section.

2.2 DMSs and Versioning

Workflows are heterogeneous, not sufficiently documented, and not automated. However, some technological solutions for collaboration exist on the market which respond to a certain amount to the stakeholders' requirements. These stakeholders generate, edit and use digital assets in the design phase and materialize them as physical assets in the construction phase. The design phase is focused primarily on digital assets and therefore has potential for digitalization of processes, but its complexity is challenging to keep under control. A CDE [1] recommends four kinds of folders or document containers for digital assets: work-in-progress, shared, published, and archived, describing their state. Using a teleconferencing system to support collaboration is proposed in [6], yet using a single proprietary software tool to realize the communication. The authors suggest several communication patterns, including one-to-one, one-to-many, many-to-one, and many-to-many, depending on how the model is accessed, edited, and shared across the participants. Authorization regarding model access is a complex topic in the AEC industry. It is most often object-based, depending on the building elements of interest, the domain, and the required task in the domain [20]. Therefore, granting access to an entire model or document might not be desired, especially in the case of a complex building model and design team constellation. Merging fragmented models or data is required for domain-specific processes, as all domains direct the information towards a single resulting product [6]. The design of a building is frequently updated, and documents and models display numerous versions throughout the workflow. Designs change on the object scale, but the technical difficulties in managing the changes on the object scale result in redundantly exchanging models or documents even in the cases of modification of only a few building elements. Four methods can be used to compare building models for design changes [21]: matching-first, comparison-first, hash-code-accelerated and quick hash-code-accelerated. The methods provide different algorithms to compare data, and the comparison accelerated with the hash code shows the most promising results. This approach however does not consider multiple software tools and the small and middle-sized enterprises (SME) involved in projects, which prevail in the AEC industry. Difficulties in addressing classifications and data structures remain, making such approaches much more challenging to implement. The focus of [22] is on the algorithm-based design including systems such as Git, a standard solution for coordinating software tool development. There are two types of version control systems: centralized and distributed. Both are relevant for the BIM-based design process, and as discussed in [22], the centralized systems may be suitable for smaller projects, while the distributed ones are suitable for the larger ones. Their work is a significant contribution to the version control during the design process; however, it only considers designers in the process and not a complete BIM environment which may display additional challenges. The algorithmic design does not correspond to BIM data management due to a core difference between code-based and object-based data management. Although [22] present an algorithmic design oriented towards BIM (and named A-BIM), the relation with BIM lacks clarity.

Automatic versioning of industry foundation classes (IFC) exports, building models defined with the open IFC standard on the object scale, is investigated in [20]. Differences between IFC models are detected in [23], naming them semantic differential transactions (SDT) to record only changed information compared with the base model. These SDT models are referenced with BC to avoid the redundant storing of building models. The authors use IFC models, with all their shortcomings recognized in the literature [24]. Their work significantly improves how the models are referenced, reducing the size of model versions and giving a basic idea of a BC connection. Still, versioning does not meet the designer requirements described in [21]. Another investigated versioning solution is the ontological representation of building models. Difficulties in assigning unique and stable identities to the numerous anonymous nodes corresponding to a Resource Description Framework (RDF) representation of IFC building models are recognized [25]. Although oriented towards the technical implementation of IFC identifiers, the issue of erroneous exports from heterogeneous software environments towards the open schema [24] is not widely discussed in [25]. Numerous concepts of building data management exist, differing by the ability of technology to record the information of a built asset. Various efforts to analyze and enhance management and versioning of building data can be found, however the ones supporting existing design processes with BC are missing. Therefore, this work considers multiple DMSs to find a suitable answer to the requirements of a BC-supported design workflow.

2.3 BC in the Design Phase

BC represents a distributed ledger technology that may facilitate the exchange of assets without a trusted third party, such as its use for cryptocurrencies. Research on using BC in the AEC industry is mostly not focused on the design but on the construction phase, where a significant amount of monetary exchange occurs [26], [27]. Using BC to support communication between stakeholders is still not sufficiently investigated. One of the papers focusing on communication involving digital information is [12], emphasizing the benefits of BC as a supplementary technology for improving design liability. The work is well appreciated for pursuing BC use in the design phase, but it simplifies data management and workflow heterogeneity. Workflow complexity represents a severe obstacle in communication processes, and improving communication flows is also a motivation for the use of BC. A framework for the design phase which uses BC is developed in [23]. To avoid information redundancy, the authors consider only design changes and store their reference using BC. They recognize problems with object IDs which are also recognized and thoroughly investigated in [25].

Although not explicitly dealing with BC implementations, information such as actor, timestamp, entity name, element ID, type of activity, and name of the modified attribute is recorded in [20] as relevant for the transactions. In their work, the authors use Autodesk Revit, and in that way, problems existing with various IDs and data management problems occurring with multiple tools vanish.

In this research, the Baseline Protocol standard is used to implement a system on the BC side, defining a framework for data and workflow synchronization called Baseline Protocol Implementation (BPI). Baseline is an emerging industry standard initiated by the Enterprise Ethereum Alliance (EEA), an association of leading organizations from different industries with the aim to drive the use of Ethereum. It defines a way to communicate on the inter-organizational scale by assuring communication correctness and verifiability using BC technologies. While data exchange is facilitated off-chain, meaning without a BC, smart contracts store cryptographic references and verify the correctness of the exchanged data. In this way, data is kept private between the interacting organizations, which is an important aspect not addressed in other solutions. [28].

3 Methodology

This research employs a qualitative analysis of data organization strategies of existing DMSs. The systems to be analyzed result from the investigation of the existing literature in Section 2.2. Several data management approaches exist, and this research aims at investigating different system types, so the following four DMSs are considered: a) file-based platform with the exchange of building-related information through a document exchange, b) IFC-object-based server, c) CDE solution Speckle, d) MongoDB system developed for the exchange between architectural design and structural analysis models.

Data management approaches can be modified to a certain degree if necessary. The novel proposals aim at providing recommendations for the overall system, serving other prototype systems and supporting different scenarios. This work seeks to interrelate and analyze the four existing DMSs - a document base platform, IFC server, Speckle, and MongoDB system - to realize an optimized design process with a BC system delivered with Baseline Protocol. As a result, a traditional planning process will be modified for adoption into the interrelated systems.

Our methodology incorporates two systems, BC-supported communication and shared data management, which will be assessed for their mutual performance in parallel with their suitability to support the design process (Figure 1). The goal here is to investigate the appropriateness of systems to facilitate traceability of shared building representation changes.

The design process might change with new technologies emerging [29], [30], [31]. However, as a starting point, an existing building design process will be considered, herein attributed as traditional, although we investigate a process using BIM authoring tools. Heterogeneity of workflows, numerous stakeholders, and non-standardized processes make it challenging to cover a whole design process [33], [32]. Therefore, we use planning scenarios from [19] as a base for system testing.

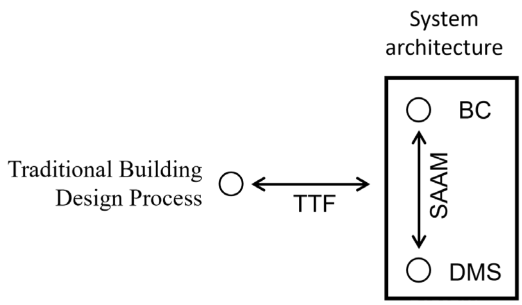

Figure 1. Methodology overview

The scenarios in [19] are described as follows:

1. a typical conceptual design scenario, with an investor, a general planer and a domain-specific planner executing tasks of creating a new design. After the generation of a new design, instructed by the investor, through the general planner to the domain-specific planner, it requires approval by the general planner and finally the investor.
2. scenario involving two domain-specific planners, where a structural building element is changed and sent by an architect for approval to a structural engineer. It involves communication on the building-element level.
3. cost calculation involving a general planner, a BIM manager, as well as a cost department employee with other domain-specific planners. The request originating from the general planner, is further concretized by the BIM manger. The BIM manager indicates required parameters and data for the domain-specific planners so the cost calculation would be optimized. With updated models, the cost department provides the calculations, which are subsequently approved by each domain-specific planer and finally the general planner.

In our methodology, the task-technology fit (TTF) model relates the building design process with system architecture. TTF is defined as the degree to which technology assists an individual in performing their tasks [34]. We identify eleven focus requirements that will subsequently be relevant as BC-supported information from scenarios described in [19]. The scenario analysis identifies a digitalization potential in each step of three scenarios, and identifies which data is required for each particular step. The requirements are investigated within four DMSs in combination with BC technology. This method, called the Software Architecture Analysis Method (SAAM) [35], tests multiple systems for their performance based on the scenarios. After testing the appropriateness of system architecture, we pursued implementing a system involving various technologies, which is described in Section 5.

4 Results

The evaluated design phase tasks are not entirely digitalized in the existing systems, although BC and various DMSs offer a spectrum of possibilities. Tasks are defined with the help of the literature review [12], [19], [35], [36], [37], [38] and serve as a filter for a detailed listing of requirements from the scenario analysis. The technology combination of BC and DMS could facilitate the following tasks:

- Allow digital assignment of tasks in the design phase
- Partially automate the assignment of tasks
- Authorize actors for activities
- Map performed activities on an independent storage
- Automatically report a performed activity
- Relate activities to a corresponding asset
- Guarantee the communicated asset based on its content
- Address assets on document (file) and building element (object) level
- Validate activity based on predefined rules

The listed tasks would significantly improve the design workflows if realized with any or both technologies. Already the systematic digitalization of processes enables further features like data analysis, which is currently not widely available in the AEC industry. However, new challenges will occur with the realization, and would need to be addressed over time. These are: more extensive energy requirements, expensive transactions, safety and security of information, rigidness of predefined methods, user-friendly interventions, scalability [3]. These challenges open new possibilities for numerous business models in the AEC industry.

With a SAAM method, three scenarios investigated in [19] delivered eleven requirements for the BC-supported design as conceptualized in [39] and requirements derived using TTF. Table 1 lists these requirements, and although a system architecture could be realized with each of the listed solutions after capturing the missing information in an alternative way, the table demonstrates the readiness of the DMSs towards the BC implementation. If a requirement is supported it means that the analyzed system in its existing form captures the needed information or provides a way to perform a specific activity. This does not mean that it is tested with various workflows and can correctly support all BIM models, but that the DMS has that functionality in its current conception, as described by the producers, answered by the users or by analyzing the DMS itself.

Table 1. Requirements for BC-supported communication (y–yes, n–no, p-partly)

Requirement	File-based	BIMserver	Speckle	MongoDB
Sender information	y	y	y	y
Receiver information	y	y	y	y
Relation between an asset and an actor	y	y	y	y
Validation of assets on file level	y	n	n	y
Validation of assets on object level	n	y	y	y
Authorization of an asset as file	y	n	n	y
Authorization of an asset on object level	n	y	p	p
Relation between activities (logs)	p	y	y	y
Report on performed activity (event)	y	y	y	y
Relation of activity and asset on the object level	n	y	y	y
Validation of activity and asset on the object level	n	n	n	n

Table 1 shows that a large part of the required information is or can be easily recorded in a certain form on diverse DMS platforms. However, none of the examined solutions provides a fully suitable scope of information. Additional information could be extracted with each solution with greater effort. An advantage is, however, recognized in open-source solutions, since the additional interventions are easily accessible. Therefore, a prototype system is further developed and demonstrated with Speckle CDE, an open-source development DMS, providing similar concepts for exchanging building data as does Git for software development. The next section demonstrates the prototype on the BC side, and its integration with Speckle.

5 Prototype Demonstration

We chose Ethereum as the preferred BC for our BPI as it is currently the most widely used BC that offers general computation. The ecosystem around Ethereum also provides sufficient additional software components, allowing an integration with various already existing systems and software libraries. Ethereum furthermore supports assigning addresses to actors, references external data with hashes, and is more generally suitable to be used by a Baseline compliant process. However, considering the constantly high transaction fees on Ethereum Mainnet, it has to be mentioned that this approach is currently not sustainable when used in practice. Improvements for using Ethereum on so-called 2nd layer networks, which accomplish a similar level of security derived from Ethereum itself, are currently in development and should be available soon [40]. These solutions provide much lower transaction fees by batching transactions together and are thus more applicable.

Our proposed BPI uses the Speckle API to implement the functionalities which are necessary for the design process. This system architecture is shown in Figure 2.

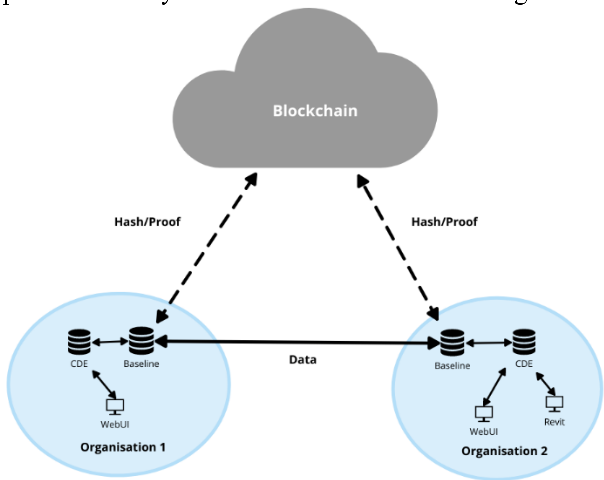

Figure 2. System architecture involving Speckle and BC

The system architecture connects existing systems of record (like a CDE) of each participant involved in the design process with the newly developed Baseline service. The Baseline service manages the data exchange between organizations. Also, it connects to the BC, where privacy-preserving proofs about the current state of both shared data objects and the overall process get stored. Interaction between the CDE, novel Baseline service, and the end-user is organized via a WebUI, which offers an intuitive possibility to follow the design process step-by-step (Figure 3). The WebUI thus abstracts technical details about the BC integration and the Baseline protocol. The novel Baseline service is furthermore able to automatically generate e-mails if required in specific process steps, e.g., to remind actors that tasks like the rework of a building element are needed. The e-mail service can also be used as an easy way to "trigger" process steps by providing data required within a specific process step. The data enters the system in the form of documents sent by the actor as an attachment. The Speckle Revit plugin provides an additional interface for BIM models and related data. Additional interfaces to the Baseline service can integrate other tools with little effort for different domains. This is especially important as AEC practitioners do not accept well overhead activities.

6 Discussion & Conclusion

The results demonstrate in which amount the tested DMS solutions are ready for implementation with BC. None of the current DMS solutions was entirely suitable for BC employment. This means, a significant effort is required for the adaptation of existing solutions to the novel technology, and the expansion of scope of the captured information for facilitating the expected tasks, ultimately generating novel technology advantages. In this research, the work was pursued with Speckle CDE, hence, giving preference to an open source solution, actively developed at the moment. Testing all four DMS solutions requires advancements of each and eventually integration with the BC system, which was not within the scope of this work.

The newly developed tool integrates BC and Speckle. The prototype is able to support basic design communication, including the model based and e-mail-based communication. The hardest problem for the wider use of the novel tool are numerous activities and interfaces with native tools that need to be correctly defined in advance. Only the predefined SCs and the correct communication with native design and analysis tools can be tested for wider application and brought to the end users.

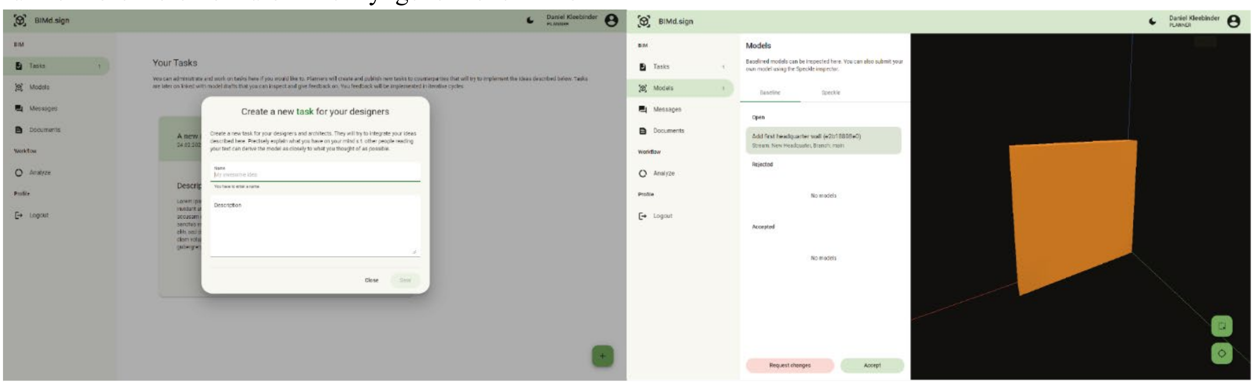

Figure 3 Screenshots of user interface in web browser connecting Baseline with Speckle: assignment of a new task (left) and model viewer (right)

This work demonstrates the use of BC and DMS to support existing design workflows in the AEC industry. Both technologies are used in a more advanced manner than found in practice. Existing research focuses on one or another technology in improving the AEC practices. In this research, both technologies' visionary implementations integrate to complement each-others features. Problems in the AEC industry are multifold, commonly grouped as people, process and technology problems [40]. Our work primarily addresses process and technology problems, and problems related to people are not within the scope. However, the proposed solution aims to minimize the overhead of design stakeholders' involvement and the influence on the existing workflows. Novel technologies are incorporated into current tools and provide additional value by capturing existing information in a suitable form. Merging the potentials of BC and DMS in a single system brings advantages such as verifiability, compliance, traceability, liability and indirectly even standardization. The recorded information further facilitates new processes and data analysis, which is currently lacking on the industry scale. This continuously improves the design process with the help of digital tools.

The main limitation of the research is the still limited applicability of the approach due to the low digitalization of the industry as a whole. DMS solutions employed for communication between stakeholders are used between domains in intra-firm workflows, with high level of trust, meaning that trust between the parties is higher than in inter-firm workflows. Using BC could increase the level of confidence in this area. However, bringing two technologies together might need a paradigm shift that could be difficult to realize, requiring a change of mindset of professionals [3]. Exploring novel business models attached to the proposal is necessary to document benefits for early adopters, thus motivating its implementation.

The following steps in the research involve primarily linking the demonstrated system directly with design tools. More scenarios will be integrated and tested, and the system will be adapted accordingly. The system needs to be verified; it is planned to provide end users with the extensions of existing tools, extract the generated knowledge, and demonstrate its use for increasing planning liability with BC. Aspects of securely managing digital objects could also be covered with non-fungible tokens (NFT) and BC, but it requires further investigation. Object-based use of DMS and process mapping in a digital form opens numerous opportunities for further improvement of the design process to deliver better performing buildings in the future. This research represents an essential initial step in the direction of object-based DMS and BC integrated solutions.

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