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# Secure and trustworthy generation of digital models of existing bridge structures using distributed ledger technology and blockchain

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*To ensure intact infrastructure systems and a long service life of bridge structures in the operational phase, the establishment of a predictive maintenance management based on digital 3D models is essential. These 3D models are often not provided, especially for existing bridge structures. In addition, their creation is very complex, resource-intensive and involves many stakeholders. Through the use of digital methods and technologies, important efficiency steps have been taken in the creation of digital models in recent years. Although semi-automated modeling of digital bridge models is possible, the quality agreed upon is not always achieved at the end of each development step.*

*In this article, an approach is developed to create transparency, safety, consistency and traceability for the generation process of digital models of existing bridge structures. The approach involves all stakeholders participating in the process and creates a decentralized control and documentation mechanism using distributed ledger technology (DLT) and blockchain. First, the current status on the use of DLT in the construction industry and bridge engineering is presented. Then, the system concept is presented and the basic algorithm is described. The general system architecture and the workflow are presented and described in models. Then the basic feasibility of the approach is presented and the previously shown concept is implemented. The basic functions of the algorithm are described and the results are critically reviewed.*

*The result of the article is showing the possibilities to use DLT and blockchain to improve the accuracy, transparency and security in the creation of digital models of existing bridge structures.*

*Keywords*: Bridge structures, BIM, Blockchain, Distributed Ledger Technology, infrastructure systems, decentralization, security, transparency

## 1. Introduction

Bridge structures are classified as critical infrastructure [1] and are important for the economy and society [2–4]. Therefore, a perfect condition of the structures and an optimized maintenance management is essential [1, 5]. This can be guaranteed by the use of digital building models using the Building Information Modeling (BIM) method as a basis [6]. The creation process of the digital models is performed manually with many sub-processes and is resource-intensive [7]. In addition, many different user groups are involved and there is a high degree of interaction [7, 8]. DLT and blockchain can be used to establish high transparency of monitoring and consistency of documentation of processes [9, 10]. In this way, all stakeholders are involved in the process chain and trust and security are increased. Nevertheless, the whole system is decentralized [11, 12]. The use of Blockchain and DLT technology ensures an efficient, secure, trustworthy and decentralized generation process [9, 10]. For the development of digital representations of bridge structures, these added values are not yet used. This article will investigate this research gap and develop a new concept for infrastructure systems.

## 2. Related Works

The use of blockchain technology has already become established in many areas. Most blockchain usage can be found in the financial sector. Here, blockchain is used primarily within transaction protocols for cryptocurrencies, in the field of smart contracting and data exchange and for financial transactions [13]. However, first results in the implementation of blockchain technology have also been achieved with regard to digital twins. In this context, the use of blockchain technology is considered to be of great importance, especially with regard to the use of digital twins in Industry 4.0. Among other things, it is stated that blockchain technology enables secure and transparent data collection in the digital twin, offers possibilities for decentralization, addresses the trust problem between the parties involved and offers potential for smart contracts based on the data stored in the blockchain and for process automatization [14, 15]. One approach provides a new concept, the decentralized digital twin concept (DDTC), to implement blockchain technology and digital twins in projects of the BECOM (building, engineering, construction, operations, and mining) industry 4.0. The DDTC aims to promote trusted, decentralized and sustainable digital twins. In this context the blockchain-technology enables secure information exchange for the project data value chain and furthermore reduces the technological challenges that would be encountered when implementing BCT and digital twins in industry 4.0 [15]. Nevertheless, the implementation of blockchain-technology in digital twins currently shows challenges. The scalability of the blockchain, for example, is an obstacle in view of the continuously increasing number of digital twins [16]. Similarly, there is the issue of interoperability between different blockchain networks and digital twins [14, 17]. It should also be noted that there are no fixed regulations or standards governing the use of blockchain and digital twins in various industries [14, 18].

With regard to the construction industry, first approaches to the use of blockchain can also be recorded. Especially for smart cities and their development the use of BCT is advantageous as it improves the implementation of defined features for smart cities and helps to achieve transparent, immutable and secure solutions. Potential fields of application are seen, for example, in citizen participation, smart contracts and secure data communication [19]. In addition, potentials can be seen in the management and storage of data. In this case the blockchain-technology is supposed to function as a public shared database for sensor data and promotes reliability, transparency and security [20]. Complementary to the use of BCT for smart cities, its use in the context of construction management is also elaborated among other things with the aim of managing any building information that is stored in files. Therefore, different scenarios for managing building information with blockchain are mentioned such as chained and very decentralized, slightly decentralized, unchained scenarios and the use of blockchain for BIM transactions by integrating it into a BIM server [16]. Another form of application of blockchain in the construction industry is its use in the context of construction inspection. Various fields of application in the context of construction inspection could be identified such as for a digital construction file, for building inspection and for a digital land file including prototypical implementation and evaluation of BCT in these fields [21]. As mentioned before the use of blockchain also offers advantages in terms of smart contracts. In this BCT can be used above all to achieve greater security and efficiency in the handling of data [22] especially when it comes to cloud computing and data manipulation in the cloud. In this case the use of blockchain-based smart contracts is intended to prevent collisions between cloud providers and customers and ensures the integrity of data [23]. However, the use of blockchain in smart contracts can also be pursued in the field of IoT. Herein the advantages of decentralization and transparency, which can be achieved with BCT, can help solve trust issues in IoT [24].

## 3. Methodology

The article addresses the development of an approach for generating digital BIM models of existing bridge structures based on DLT and blockchain. It includes the three sections - (i) related works, (ii) concept development and (iii) implementation. The first step is to define the status quo with a literature review to reflect the use of DLT and Blockchain technology in general in the construction industry and specifically in the field of infrastructure construction. In this process, the relevant literature is analyzed and the state of the art is defined. In the second section, the concept for secure and transparent generation of digital BIM bridge models using DLT and Blockchain is developed and explained. To specify the approach, a system model is developed to represent the basic architecture. Furthermore, a sequence diagram is modeled to represent the process structures and interactions between the stakeholders and systems. For a better understanding of the used algorithms, the included functions are explained and a pseudo code for two process sequences is presented. In the third part of the article, the approach is implemented in a minimized prototype to demonstrate the basic feasibility. Thereby, the use of DLT and blockchain is implemented and tested of the generation approach. Finally, the results are discussed, critically reflected and a research outlook is presented.

## 4. Development of the DLT-Concept

In the previous two chapters, the status quo was defined and the methodological approach of the article was presented. Subsequently, the conception of the blockchain approach for the generation of digital models of existing bridge structures is presented. Thereby, the general process of the model generation and the involved stakeholders are described in the first subchapter. This is followed by an explanation of the integration and use of Blockchain for the model process. On the one hand, a system model of the integration of a blockchain platform into existing structures is explained and the individual system components are described. On the other hand, the adapted and novel evolved structures of the workflow are presented in a sequence diagram. This enables an understanding of the interactions occurring between the individual participants and the applied system. In principle, the approach presented in the article is developed on the basis of [9] and is supported by the existing special features of the bridge construction sector and the BIM method.

### 4.1. *General Process of the model generation*

The basic procedure for generating digital and semantically enriched BIM models of existing bridge structures is based on [8] and is subdivided into five phases: (i) order placement and basic definition, (ii) scanning, (iii) geometric transformation, (iv) as-built data analysis and semantization, (v) platform integration and (vi) external approval for use. A total of five stakeholders are involved within the approach. The main responsibility for the procedure lies with the bridge operator (role: asset owner). In addition, a BIM manager exists on the client side for supervising the generation process and the internal quality audits (role: BIM Manager). Furthermore, a surveying company (role: Surveyor) is involved on the contractor side for the scan of the bridge, and an engineering company (role: BIM Engineer) is involved for the creation and semantization of the BIM model. The public construction authority (role: Public Authority) is involved as an external party for external acceptance and approval for use.

In the first phase (Phase 01: Placing of order and basic definition), the order for the model creation is placed by the asset owner with the surveyor and the engineering company. Subsequently (Phase 02: Scanning), the existing bridge structure is recorded holistically by the surveyor using different laser scanning methods. The resulting scan data is then processed, homogenized and fused into a "master point cloud". Afterwards, in the third phase (Phase 03: geometric transformation), the master point cloud is transformed by the surveyor into a digital 3D model. This process step can be performed manually [25, 26] or with the support of intelligent algorithms [7, 8, 27]. Parallel to this, the fourth phase (phase 04: as-built data analysis and semantization) first focuses on the acquisition and analysis of as-built documents. In this case, the BIM engineer uses intelligent algorithms to analyze and interpret relevant semantic information in the building documentation and maintenance management system. In the next step, the data is integrated or linked into the digital geometry model of the bridge from phase 03. In the fifth phase, the semantically enriched 3D model is then subjected to an internal quality control by the BIM Manager and, if the agreed quality is fulfilled, transferred to the open data exchange format "Industry Foundation Class". The model is further integrated into a Common Data Environment, serving as a central project platform that can be used by all parties involved (Phase 05: platform integration). At the end, the BIM model of the bridge is checked once more by the public construction authority and validated for the official use in the operational phase (phase 06: external approval).

### 4.2. *Structure of the Blockchain approach*

After establishing a basic understanding of the process of generating models of existing bridge structures and the stakeholders involved, an approach using DLT and blockchain is concretized for decentralized quality assurance and illustrated in the system model (see Fig. 1). Each project participant becomes a user of the Blockchain (Blockchain Stakeholder). This increases the Blockchain to a total of five stakeholders at the beginning and is set up as a hybrid Blockchain (source) within the DLT platform. This enables the possibility of a subsequent integration of additional users and extension of use into the operational phase. The DLT platform contains the components of the blockchain resources and the smart contracts. The blockchain resources include all relevant components of an individual block in the chain. On the one hand, this is the own hash and the hash of the predecessor blocks (previous hash). A hash is an unchangeable character string that acts as the identification number of the block. On the other hand, the block provides a timestamp and information about the model owner, the current user or the person responsible for the phase, as well as the description of the current process phase. [28] The block also contains a log for documenting all actions performed and changes made with the chain used within the previous phase (Provenance data protocol). For the blockchain approach, all contractual agreements between the project participants are managed in the form of smart contracts in the DLT platform in addition to the processing of real contract documents.

Further data sets on the structure (e.g. structure management system, as-built documentation, etc.) and data generated in the phases (e.g. point cloud data) are stored in further databases. These

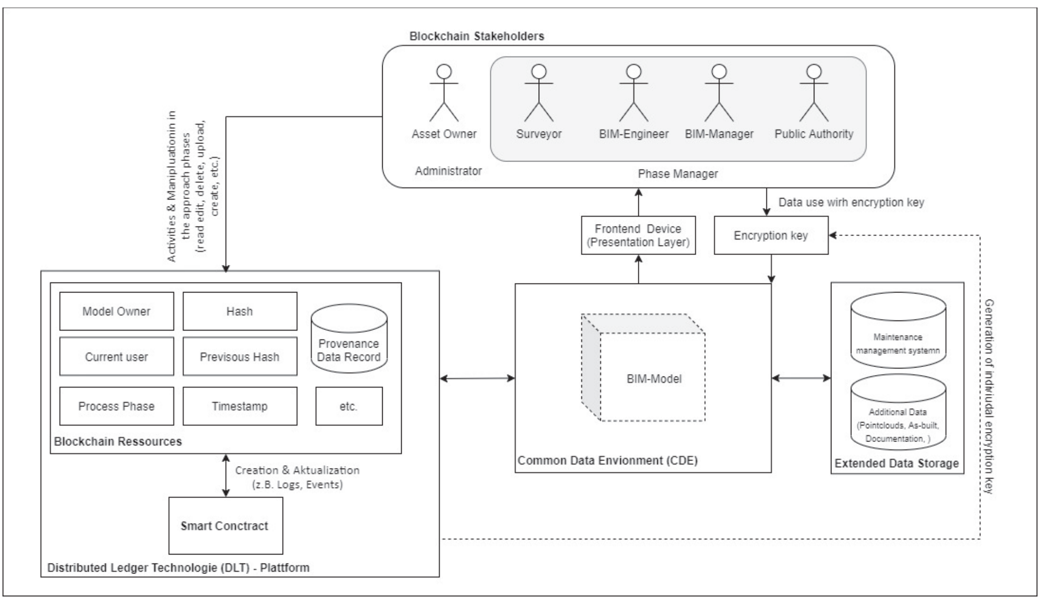


Figure 1 System architecture of the approach

are linked to the CDE and can only be accessed by project participants via the CDE using generated encryption keys [29, 30]. The DLT platform generates these keys for each registered user of the blockchain. The CDE also stores and manages the BIM model of the bridge structure at the end. In the application scenario of generating digital models of existing bridge structures, each phase of the procedure receives its own block in the blockchain. Only when all parties involved in the blockchain agree to the required quality at the end of a phase the data is uploaded to the CDE and the next phase can start. If there are reservations at the end of the phase, the quality of the results achieved needs to be clarified and optimized before the procedure can progress further.

### 4.3. *Sequence of the Blockchain approach*

In addition to the basic architecture of the blockchain-based approach, the sequence of the generation process and the algorithmic functions are also significant. This is examined in more detail in this section and illustrated in a sequence diagram (see Fig. 2). In this diagram, all six main phases of the generation process are integrated and, for compact comprehensibility, only the most relevant sequences of actions between the individual parties and systems are shown.

The overall responsible party over the DLT platform, the blockchain, the smart contracts and the flows is the asset owner. Each additional participant receives exclusive access to the DLT platform with an individual, crypted user address. Nevertheless, each user has an individual encryption key generated by the DLT platform for access and data retrieval on the CDE. In conclusion, only authorized groups of people are able to participate in the generation process of the BIM model and to use data from the CDE. All activities performed during the generation process are tracked on the DLT platform and stored with logs in a transparent and traceable manner. When a main phase begins, the DLT platform notifies all project participants of its start. In contrast, the successful completion of a single phase ("ApprovesSuccessful") is also reported to all stakeholders involved and forms the transition to the next phase. To initiate a confirmation message, the actptance of each individual stakeholder is required in advance. This confirmation is activated within the DLT platform and described in the sequence diagram in generalized form with the action

*"AcceptanceOfAllStakeholders()"*.The individual phases and their associated functions are described in detail below:

Phase 01: placing of order and basic definition

The main asset owner is also the initiator of the generation process and directs it to the DLT platform with the function *"CreateBIM-Model()"*. Afterwards, a project room is created in the CDE by the responsible person (*"CreateProjectRoom()"*) and orders are sent to the other project participants (Surveyor, BIM Engineer and BIM Manager) (*"ContractandOrder()"*). This is followed by the confirmation of the agreed quality by all involved stakeholders ("AcceptanceOfAllStakeholders()"). With the message *"AssetOwnerOrderedCreationBIM-Model"* the transition to the second phase takes place. Prior to this, consent is required from all other parties via the DLT platform.

Phase 02: scanning

The second phase starts with the initialization of the surveyor's scanning via the *"InitiateScanning()"* command. As a result, all parties involved receive a message. After the scan data is stored on the CDE (*"StoreScandata()"*), the quality control of the scan data is performed by the BIM manager, *"ApproveQualityofScandata()"* Provided the quality is accepted by the BIM manager and all other parties give their consent via the DLT platform (*"AcceptanceOfAllStakeholders*()*"*), the phase is completed. This phase is terminated with the platform reporting *"ScanningSuccessful"* to all blockchain stakeholders.

Phase 03: geometric transformation

The third phase again starts with an initiation command *"InitiateGeometricTransformation()"* and the broadcast message to all stakeholders (*"StartGeometricTransformation"*). After processing the scan data to a digital BIM model, its metadata is stored in the CDE (*"StoreGemoetrixMetaData()"*) and again a quality control is performed by the BIM Manager *"ApproveQualityofGeometricMetaData()"*. At the end of the phase, the confirmation of all parties involved is again obtained (*"*AcceptanceOfAllStakeholders()*"*) and the finalization is performed by the platform notification *"Geoemtric TransformaionSuccessful"*.

Phase 04: as-built data analysis and semantization

After the start of the phase by the BIM-Engineer (*"InitiateAsbuiltDataAnalysisAndSemantization()"*) the as-built data is stored on the CDE and the procedure is run. After successful semanticization, the attributed model is stored on the CDE (*"StoreSemanticizedModel()"*) and the quality check of the BIM Manager (*"ApproveQualitySemanticizedModel()"*) is performed. Next, the phase is completed with the receipt of all confirmations in the DLT platform (*"AcceptanceOfAllStakeholders()"*) and the notification is sent to all stakeholders (*"As-builtAnalysisandSemantizationSuccessful"*).

Phase 05: platform integration

In this phase the model is transformed into an open data exchange format and integrated into the platform. The phase starts with the initiation of the BIM manager (*"InitiatePlatformIntegratio()"*) and the subsequent confirmation at the end of the process (*"ApproveIntegrationAndOpenDataFormat()"*). Subsequently, the approval of all project participants is required

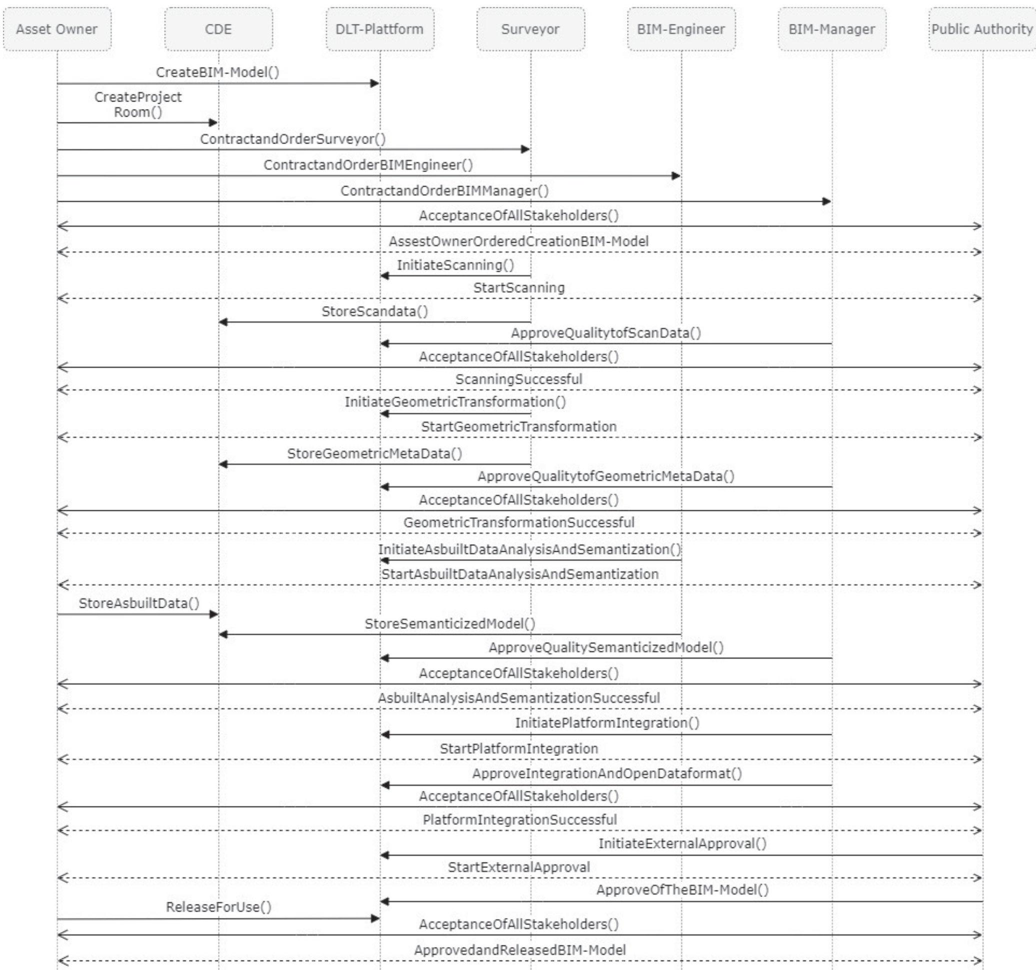


Figure 2 Sequence model of the blockchain approach

(*"AcceptanceOfAllStakeholders()"*) before the phase is completed via the DLT platform with the statement *"PlatformIntegrationSuccessful"*.

Phase 06: external approval

Before the official use of the BIM model in the utilization phase, the external quality assurance and approval by the bridge construction authority takes place. This process starts by the initialization command (*"InitiateExternalApprovel()"*) followed by the approval when the necessary quality criteria are met (*"AcceptanceOfAllStakeholders()")* and the confirmation message is delivered (*"ApproveOfTheBIM-Model()"*). After that, the asset owner releases the model by using it (*"ReleaseForUse()"*).

The sequence diagram represents the necessary interactions between the project participants and the application systems very well (CDE, DLT platform). The process is shown as an optimal sequence. This runs smoothly as long as all project participants confirm all phases even when using the block grove and DLT platform. This ensures the integration of all participants in the complete workflow and guarantees transparency. If a user's confirmation request from the DLT platform is rejected, a phase must be run through again. This can result in delays.

## 5. Implementation

After the description of the basic concept in the previous chapter, the approach is implemented in a first prototype as a minimal example. This is used to demonstrate the feasibility and practicability of the approach, which is followed by the initial development of an algorithm for the blockchain. It contains all phases of the generation process and represents all project participants. The setup of the DLT platform including smart contracts, as well as the linkage with a CDE are not yet considered in this article. For the programming of the blockchain, the object-oriented programming language Python is used. Each phase receives its own hash, a timestamp and a hash of the previous phase. After converting the concept into an algorithm, the basic implementation of the concept can be confirmed. The result of the first blockchain for the generation of digital models is illustrated in Figure 3. A coherent chain of individual blocks was generated. Furthermore, all blocks of the chain have the identical hash of the previous block. This confirms the functionality of the system. It also ensures the decentralization of the approach and creates a uniform transparency for the generation process of the digital model of existing bridge structures.

## 6. Discussion & Conclusion

The article presents an approach to generate digital BIM models of existing bridge structures using DLT technology and blockchain. At the beginning, the status quo was presented by means of a literature review on the topics - (i) blockchain and digital twin and (ii) blockchain in the construction industry. This is followed by the conceptual design of the approach. In this context, first the basic procedure of the process to generate BIM models of existing bridge structures was presented, divided into main phases and the project stakeholders. Subsequently, a system architecture was designed and described to represent the basic components for the blockchain-based generation approach. To represent the system interactions and algorithm flow, the definition of individual functions in the system and their systematic flows, represented in the sequence diagram. In the next step, prototype and a functional algorithm was developed. This step establishes the basic feasibility and practicability.

The approach can provide increased transparency and decentralized quality assurance for critical infrastructure generation. This increases security in the generation process and trustworthiness in digital models in operation.

```
Phase_01: PlacingOfOrderandBasicDefinition Responsible Party: Asset_Owner Participant: Surveyor Block 1:
9b0c8cab1f3295ba3f6ae9cf7dd9c066487f77470d3565c30a748a6225422e56
Phase_02: Scanning Responsible Party: Surveyor Participant: BIM-Manager Block 2:
e6799fdb7f95c97c20290ace88009f237c98396e03e42be319665830a40143c7 Previous Block:
9b0c8cab1f3295ba3f6ae9cf7dd9c066487f77470d3565c30a748a6225422e56
Phase_03: GeometricTransformation Responsible Party: Surveyor Participant: BIM-Manager Block 3:
19cfc207022edb4ec88995db52e6ca6f5525f78663b9474cf0453ef632e37339 Previous Block:
e6799fdb7f95c97c20290ace88009f237c98396e03e42be319665830a40143c7
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Existing limitations of the system is the singular implementation of the blockchain, as a component in the overall system. In addition, no testing was done in the context of a case study on a real demonstrator. These points will be considered and implemented in future research activities of the authors. Fundamentally, the article provides an approach for the decentralized generation and subsequent use of digital models of critical infrastructure systems. Furthermore, the approach increases the level of automation and security and promotes collaboration and trust among stakeholders.

Figure 3 Extract of the result of the blockchain algorithm

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