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Chapter

Blockchain-Based Data Integrity for Collaborative CAD

Samir Lemeš

Abstract

Distributed and collaborative computer-aided design (CAD) environments include building information modeling (BIM) and geographical information systems (GISs) in civil engineering and architecture, or product data management/product life cycle management (PDM/PLM) in mechanical engineering. It is essential to keep the data integrity in these computer applications as it contributes to building users' confidence in CAD/BIM/PDM data. Blockchain technology, the core foundation of cryptocurrencies, is increasingly being used for other purposes and could solve the data integrity issue in collaborative CAD environments. However, it has some disadvantages such as the transparency of data and the slowness of storing data in the blockchain due to distributed consensus. Increasing demand by the Industry 4.0, IoT, Smart Cities, and other initiatives could foster the best what blockchain has to offer: data integrity, reliability, and traceability. This chapter explains how blockchain works, how can it be utilized in distributed CAD environments, what are the major challenges for implementation, and how CAD vendors could use it to increase CAD data integrity.

Keywords: blockchain, CAD, BIM, PDM/PLM, data integrity

1. Introduction

The increasing complexity of modern engineering products requires new paradigms and leveraging any available technology to keep in pace with the competition. Increasing market demands such as environmentally friendly products, sustainable buildings, dynamic global supply chains, cost reduction requirements, and workforce mobility have changed most steps in the product life cycle process (design-manufacturing-control-utilization-decommissioning). Even the most individual creative tasks such as product design now require teamwork to deliver products on time. It is not unusual to have globally distributed teams working on any single engineering task. These teams use the advantages of cloud computing to collaborate and share skills and resources. Simultaneously, the software vendors keep shifting their products from computer workstations to cloud computing resources, thus enabling globally distributed teamwork, but introducing the new challenges.

The use of cloud computing in computer-aided design (CAD) is still not mature enough to prevail over desktop computing. Computer-aided engineering (CAE) applications do make use of cloud computing to overcome the computing power limitation of computer workstations to perform resource-demanding simulation tasks. Collaborative CAD environments such as building information modeling (BIM) and product data management/product life cycle management (PDM/PLM)

have already embraced the advantages of cloud computing, which brought another issue—the problem of information security. This issue could be resolved by using emerging technologies such as blockchain.

Although several top-tier software providers offer blockchain-based solutions: Microsoft Azure Blockchain service, SAP Leonardo Blockchain, Amazon Blockchain as a Service, IBM Blockchain Platform, and Oracle Blockchain Cloud Service; the major CAD software vendors still hesitate to leverage blockchain in their BIM/PDM/PLM solutions, and they are still waiting for what small start-ups will have to offer in a near future [1].

London-based engineering consultant company, ARUP, has been studying blockchain since 2013. Their research indicates that early adoption within the architecture/engineering/construction (AEC) industry might not begin before 2025 [2]. An American international technical professional services company, Jacobs Engineering Group, cofounded the Integrated Engineering Blockchain Consortium (IEBC), which launched its CoEngineers Blockchain in 2018 [3]. The first integrated BIM and blockchain application is still under development in the Spanish technological research and development project, DELFOS [4].

A French start-up technology company, Lutecium, started to develop a blockchain-based software, BIMChain, aimed to accelerate the BIM for the construction industry [5, 6]. Their solution, based on an Ethereum-based platform, integrates BIM ecosystem through dedicated plugins for Revit or ArchiCAD. It increases BIM data quality through accountability and incentive mechanisms, transforms BIM into a collaborative and legally binding process, and provides traceability. The project is supported by the Autodesk and the French task group Plan Transition Numérique dans le Bâtiment. An early beta version of the software was launched at the beginning of 2019. Their ambition is to create a collaborative process bridging the gap between 3D CAD models and legally binding paper-based formal processes related to project management, building maintenance and control, and insurance and payment. They aim to link validated proofs of contributions to 3D CAD models with a form of smart contract, thus making BIM data contractual.

2. Collaborative CAD environments

The National Institute of Standards and Technology (NIST) defines cloud computing as "a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction" [7]. These resources include computer networks, servers, storage, applications, and services. In other words, cloud computing is shifting the computing power, data, and management from the local computers and workstations to a globally accessible network of computer resources. This technology helped users to make the data and software globally accessible and enabled teamwork and collaboration in any computer-aided task.

CAD only recently started to use the advantages of cloud computing. **Figure 1** shows how engineering design collaboration evolved from traditional paper-based documentation to modern cloud computing solutions. Personal computers did leverage the expansion of CAD into every engineering office but initially lacked the collaboration features. They were introduced gradually, first over the local file sharing, then using internet servers, gradually increasing the ratio of data and software stored online, converging toward completely cloud-based solutions.

Cloud computing is increasingly making web-based synchronous CAD commercially available. Multiple designers are now able to simultaneously modify a

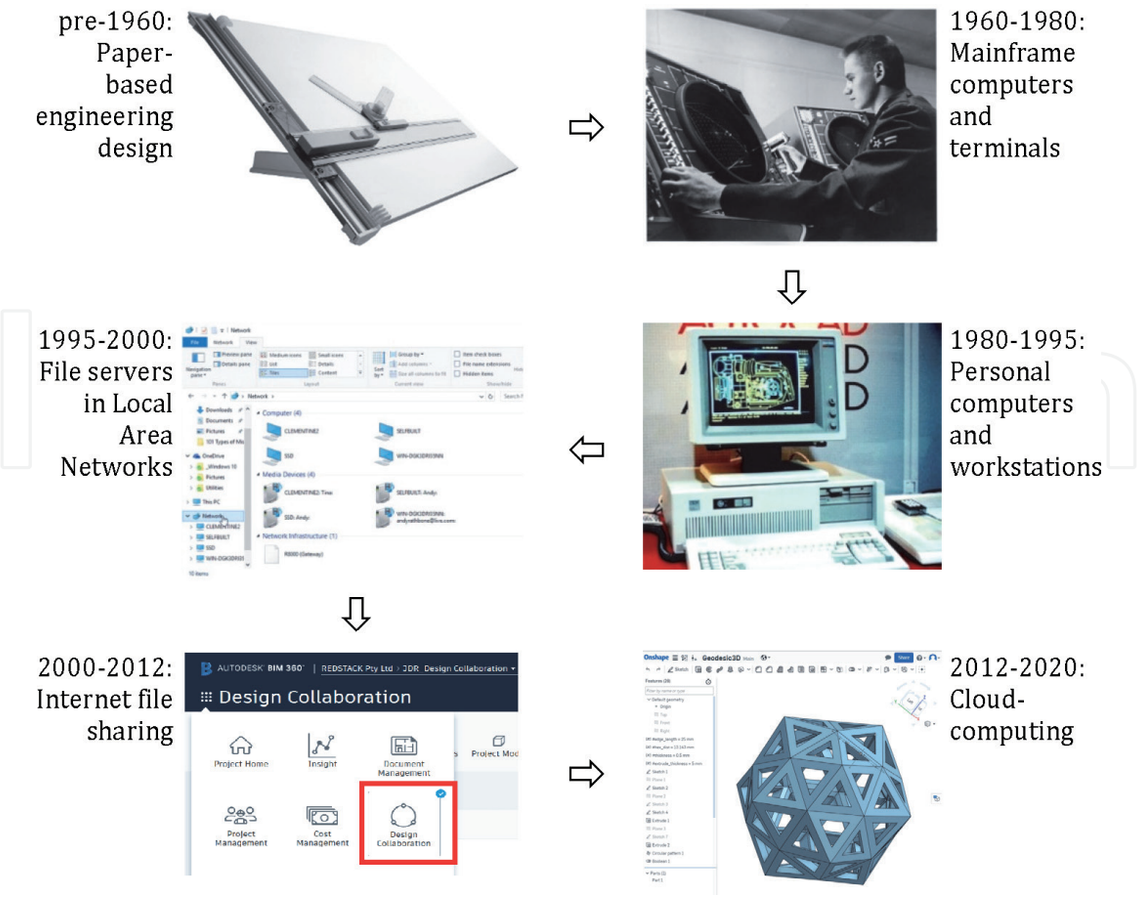


Figure 1.
The development phases of CAD.

model from their workstations. CAD platforms now offer benefits like synchronous access, cost-effectiveness, higher utilization of resources, and enhanced security, while still having unresolved issues related to usability, security, and computational performance [8].

Another CAD-related technology, computer-aided manufacturing (CAM), was limited for decades to using CAD files to generate code for machining, and it was boosted recently by the rapid expansion of 3D printing (sometimes referred to as additive manufacturing) technology. As a vast number of digital models ready for 3D printing are available in cloud-based repositories, there is a risk of intellectual property (IP) infringements by enabling cheap manufacturing of counterfeit products or simply of altering these files. Open issues could be solved by integration of the blockchain in additive manufacturing supply chains, provided that the technology is available and affordable [9].

2.1 PDM/PLM

Product data management (PDM) is a specialized information system developed primarily to manage CAD design files and CAE simulation results. It represents the extension of 3D CAD models to a specialized design environment that manages a set of CAD files in hierarchically distributed files.

The product life cycle management (PLM) concept emerged from PDM by providing services to extend the product design data to manufacturing and operations [10]. PLM manages the complete product life cycle, usually in a networked or, more recently, cloud environment. In PLM, multiple users have access to CAD models stored in the database rather than in individual files stored locally or on

dedicated servers. CAD files in the PLM database are only one of the set of attributes describing a machine part, machine assembly, or entire construction. PLM systems connect intangible to physical asset information managed by enterprise resource planning (ERP) and customer relationship management (CRM).

An analysis presented in [10] suggests that PLM is based upon the three fundamental concepts. According to [10], these concepts enable (1) product definition and related information being used and managed universally and securely; (2) product definition and related information being maintained throughout the entire product life; and (3) business processes being managed and maintained, enabling creating, managing, communicating, and using the product and related information. The product information can thus be shared to all stakeholders in the product life cycle, from design, manufacturing, assembling, quality control, sale, operation, and disposal or decommission at the end of its useful life.

Most CAD/CAE software vendors also have the PDM/PLM solutions, such as Siemens Teamcenter (**Figure 2**), Autodesk Fusion Lifecycle, Dassault Systems Enovia, Aras Innovator, PTC Windchill, and SAP. Despite that, not more than one third of CAD users use PDM/PLM to create Bill of Materials for their CAD drawings. Most users still use spreadsheets to create Bill of Materials. It can be concluded that this technology is rather emerging than mature [1].

The deployment of PLM platforms, used for handling the product data exchange, is quite costly, and very often, small companies cannot afford them. When such companies become part of larger original equipment manufacturers' (OEMs) networks, the PLM platforms used typically belong to an OEM and the transparency of the information contained is limited. Besides, these platforms represent the possible attack pints compromising the security of the PLM. Security and transparency could be increased by using the blockchain technology [11].

2.2 BIM

As PLM is used in the mechanical engineering sector, such as automotive and aerospace, BIM is used by the architecture/engineering/construction industry to collaboratively manage a virtual representation of the physical facilities. The difference between PLM and BIM is in the fact that the mechanical engineering sector is more globalized and consolidated industry; by contrast, a majority of construction

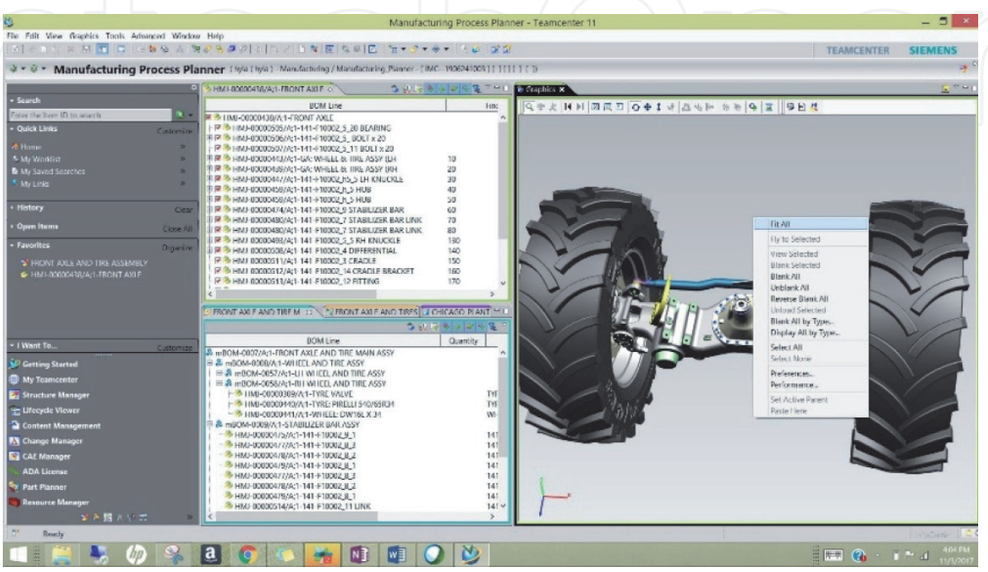


Figure 2.
Siemens Teamcenter (source: www.plm.automation.siemens.com).

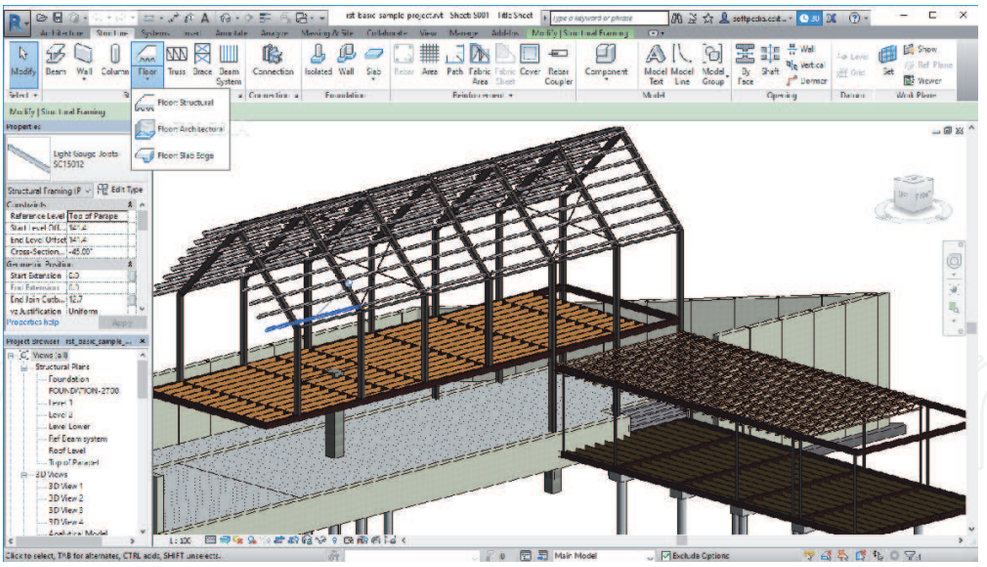


Figure 3.
Autodesk Revit (source: www.autodesk.com).

projects remain rooted in local contexts [10]. The level of automation is also different in two sectors, and BIM is generally characterized by the low level of information technology (IT) implementation. The main perception of the construction industry relative to BIM implementation challenges focuses on answering many of the same data exchange, business process and policy phasing problems that have faced PLM deployment [10].

Both PLM and BIM emphasize open communication and information exchange, collaborative decision-making, early participation and contribution of knowledge and expertise by downstream stakeholders (contractors and suppliers), and greater levels of risk sharing [10]. However, BIM has not yet solved issues of trust, reliability, and transparency [12].

BIM platforms, such as Autodesk Revit (**Figure 3**), originally or through external plug-ins, can be used to simulate the real-world conditions of the building, including geography, seismic data, weather conditions, sun position, and lighting. They also tend to integrate more advanced tools such as structural analysis, energy audit, seismic behavior, etc. The review presented in [13] suggests that BIM could be developed in a near future in such a way that all design and analysis tools are contained in a single software platform, most probably in the cloud computing environment.

This technology is emerging, and basic definitions are being upgraded and updated [1]. The main purpose of **BIM 3D**, based on the 3D CAD geometry, is **visualization**. The next generation **BIM 4D** adds **time**-related data and facilitates programming. When **costs** are included, it is considered as **BIM 5D**. **BIM 6D** adds product **operation** and facilities management to 3D CAD objects, enabling the monitoring of the product **sustainability** (sometimes referred to as **BIM 7D**) and product performance. BIM 7D (or **BIM 8D**) embeds the **safety** and emergency plans to prevent security issues.

3. Blockchain

Blockchain is a digital, replicated ledger of transactions that are secured against alterations once the peer-to-peer network has validated and added the transaction to all instances of the ledger [2], allowing traceability and accountability.

Blockchain will likely affect most business processes requiring a trusted digital environment. The term was coined in 2008 by "Satoshi Nakamoto" (it is still unclear whether it is a person or an alias for a group of persons). Initially, it was meant to act as the public transaction ledger used by the cryptocurrency, Bitcoin. New applications of that system keep arising. Blockchain can be described as a simple distributed and decentralized database of transactions or contracts, chronologically stored across a wide computer network, without centralized management and a single managing authority [1].

Technically, blockchain relies on three well-known IT concepts: peer-to-peer networks, public key cryptography, and distributed consensus based on the resolution of a random mathematical challenge. The combination of these concepts allows a breakthrough in computing.

Blockchain creates fixed-size blocks of information using so-called hash functions. These blocks are then added to an array called a blockchain. Each new block is encrypted irreversibly using a hash function and then shortened to make the fixed-size output. The chain of blocks thus contains the encrypted version of the complete history of changes of all blocks. The blockchain information is prone to changes, as any change in any data transfer phase would irreversibly alter the final output. One can say that blockchain disables the famous "undo" function.

The blockchain relies on cryptographic hash functions. They are mathematical functions creating the fixed-size bit-string output (hash). It is nearly impossible to guess the length of the hash if someone tries to decrypt the blockchain. The hash algorithm produces a unique output and it is a one-way function. A Bitcoin and Ethereum blockchain both use SHA-256 (secure hash algorithm), developed in 2001 by the National Security Agency (NSA) in the USA.

The family of cryptographic hash functions include [1] the following: 224–512-bit BLAKE (BLAKE2, BLAKE3), Merkle tree-based 128–512-bit message digest algorithm (MD5, MD6), 128–320-bit RACE Integrity Primitives Evaluation Message Digest (RIPEMD), 224–512-bit secure hashing algorithm (SHA-2 also known as SHA-256 or SHA-512, SHA-3), Russian 256, 512-bit Streebog, etc. These hash functions are implemented in programming languages as classes, which can contain more different algorithms. These hash functions differ slightly in the way they create output from a given input data and in the length of a produced output (number of bits). **Figure 4** shows an example of a hashed filename. If only one letter in the file name is changed, the MD5 hash function gives an entirely different hash digest. The same is valid for any other information, but the hash digest always has the fixed 128-bit size (32 characters in hexadecimal notation).

Information stored in the blockchain cannot be altered or lost. It replicates into the same number of copies as there are nodes in the network. The blockchain stores the complete history of all previous states of information stored. In that way, anyone could check the final state validity simply by using the same hashing algorithm to all information from the beginning to the end. The blockchain uses hash functions to encrypt information and to digitally sign the information from all previous steps. Hash functions are much older than blockchain, and they were used



Figure 4.
Using MD5 hash function for irreversible data encryption.

to encrypt data for decades. A good hash function has some main characteristics as follows: (1) The hash value is fully determined by the input data and gives unique result for any input, (2) Even though the output has fixed length, the hash function uses all input data, (3) The hash function "uniformly" distributes the data across the entire set of possible hash values, (4) The hash outputs of similar strings are very different, (5) The hash function is computationally efficient, and (6) The hash does not reveal any information about the input.

3.1 How does blockchain technology works?

Blockchain (with a capital B) was originally defined as the electronic ledger for Bitcoin. Today, blockchain (lowercase, as in blockchain technology) is most easily defined by an example [14] as follows:

- Some data is stored in a Microsoft Excel workbook. This file can be shared with collaborators as an e-mail attachment. Any change made by collaborators needs to be returned by e-mail and then merged with the original document. If there are more collaborators, this makes the process cumbersome and increases chances of error.

- Cloud-based sharing services such as Microsoft Office365 or Google Sheets can be used to overcome this problem. Collaborators do not receive an e-mail attachment but only a link to the online file. More collaborators can update the spreadsheet simultaneously, and there is a version history showing what changes are made by whom and when. This sounds much better from a collaborative point of view, but there is still a chance that any user with enough credentials can erase or alter the file in the cloud. A blockchain can provide a solution to this problem.

Blockchain is also the cloud-stored shared information but is duplicated thousands of times across a network of computers, which has been designed to regularly update this sheet. Information held on a blockchain exists as a shared and continually reconciled database (i.e., once every 10 min). Each group of transactions in the database is referred to as a block which cannot be altered once added to the chain.

Blockchain security relies on encryption, based on the public and private keys. The keys are long, randomly generated strings of numbers. The public key represents a user's ID on the blockchain, and the private key, which must be safeguarded, is used to digitally sign the transaction, providing for data traceability and integrity.

Figure 5 shows how each block in the blockchain contains the cryptographic hash of the previous block, which cannot be changed. Each next block strengthens

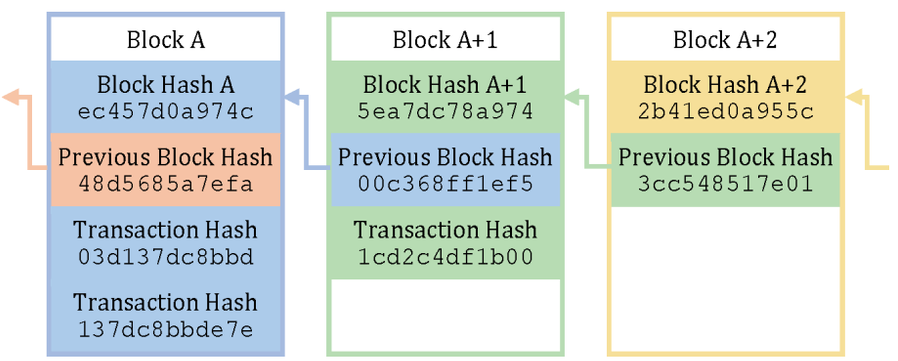


Figure 5.
The sequence of the hash value in the blockchain.

the verification of the previous block and the blockchain's security. Adding new blocks increases the reliability of the blockchain.

The blocks contain public data, such as product ID, user manuals, disposal, and recycling guidelines, and transaction data, such as CAD files, technical and material specifications, mechanical properties, assembly instructions, requisition orders, signatures, and cryptography keys [11].

The blockchain consists of linear sequence blocks, which are added to chain with the regular intervals [15]. The information in the blocks depends on the blockchain network, but the timestamp, transaction, and hash exist in all the blockchain variants. The blockchain relies on several specific mechanisms such as PoW, PoS, PBFT, and delegated proof-of-stake (DPoS) [16, 17].

The proof-of-work (PoW) mechanism works by determining the node that writes a block on ledgers. The nodes in the network compete to solve a mathematical puzzle (generally a computationally complex but easily verifiable pattern) to record a transaction. After the puzzle is solved, other nodes in the network reach consensus by broadcasting the solution. The two most popular blockchain systems, Bitcoin and Ethereum, operate on the PoW mechanism, involving extensive computing power and cumbersome mining processes to create new blocks.

The proof-of-stake (PoS) mechanism chooses the creator of the block in a deterministic method. It requires the credibility of data, denoted by proof of ownership. This method operates solely on transaction fees.

The practical Byzantine fault tolerance (PBFT) algorithm, used by Hyperledger Fabric, is a consensus method that can tolerate a maximum of 1/3 malicious byzantine replicas. A primary is selected in each round and is responsible for ordering the transaction. PBFT requires each node to query other nodes.

The delegated proof-of-stake (DPoS) algorithm lets stakeholders elect representatives to validate blocks. Since this mechanism features a smaller number of nodes, the transaction processing is faster.

Figure 6 illustrates the processes of signing and verification of blocks in the blockchain. The process is based on the private/public key cryptography. Each transaction is verified by the previous block owner's public key and signed by his private key. The hash function ensures data integrity as it is irreversible.

Common uses of blockchain now include financial services (payments, money transfer, customer benchmarking, and full trade life cycle management), supply

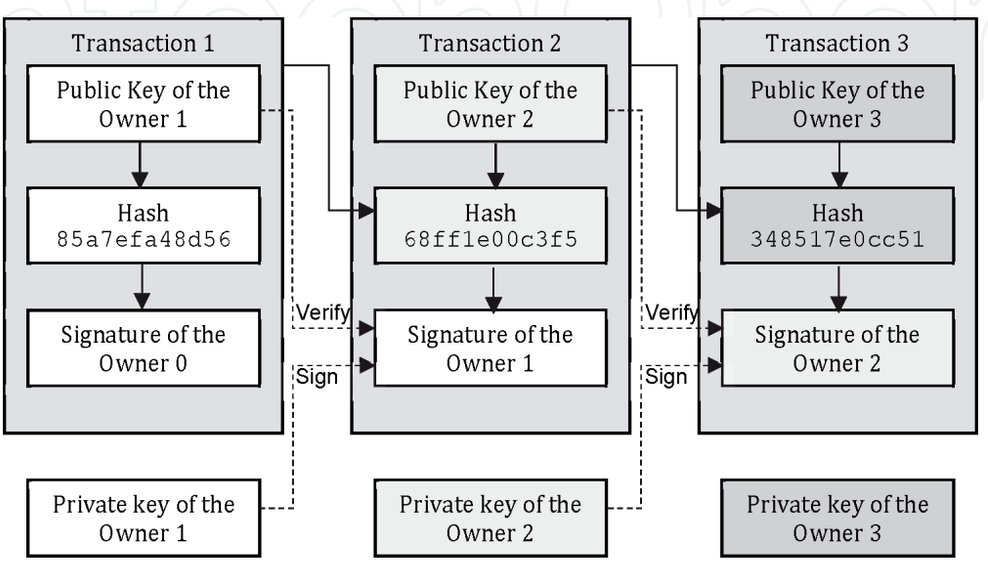


Figure 6.
The signing and verification in the blockchain.

chain (traceability of product components, electronic compliance records, patent-pending, quality control data, and non-repudiation of IoT sensor data), public sector (government-managed personal data records, import/export customs and taxes, regulatory certifications, and digital citizen identity), and health care (personal health records, credentials of service providers, and clinical data). This list is likely to expand, and new applications appear daily. This makes blockchain a "solution seeking for problems that need to be solved."

4. Utilizing blockchain in distributed CAD environments

As more available resources and stakeholders are involved during the product life cycle, the exchange and management of product-related information become a challenging task, affecting significantly the intellectual property protection process as well as the distinction of roles among stakeholders [11].

In a modern engineering environment, projects rely on teamwork, where team members with the same or different experience, skills, and function have to collaborate intensively. Very often, team members do not share the same office space, and sometimes they are globally distributed. This increases the need for reliable and traceable data. Traceability, in this case, means that each change in an engineering project can easily be attributed to a team member who made it and who "owns" the process step. All team members have to have their digital signature. Using cryptographic hash functions to encrypt data and blockchain to make it change-proof keeps the complete supply chain transparent, reliable, and traceable.

If there is a centralized authority providing traceability and reliability of data, this would make the information vulnerable to external attacks. As blockchain is decentralized and distributed, it becomes very secure, traceable, and reliable.

Figure 7 shows an example of how blockchain can be used to enable data integrity in the product development process. Each block consists of public data and encrypted transaction data. Both data is hashed and stored in encrypted form, the signature contains the timestamp, nonce, and each block contains the hash from the previous block. The term nonce is used to describe an arbitrary number called "number used once" or "number once," which is used with the timestamp to add another level of difficulty [18]. If any unauthorized data alteration is made within the process, the resulting blockchain is compromised and the owner is aware that changes have been made. The blocks are distributed within the network of users, thus eliminating the need for a single verification authority.

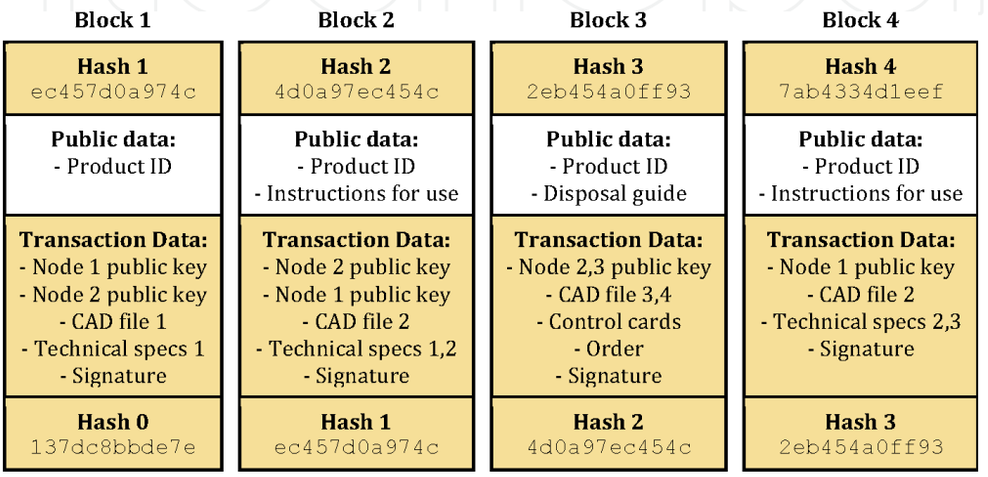


Figure 7.
The blockchain primer for CAD-based development process.

Some potential uses of blockchain in construction are mentioned in [19]: storing sensor data from buildings in a trustworthy and distributed way, maintaining records of digital property, timestamping acts or transactions, automated dispute resolution and smart cities, and in real estate investment. The same authors suggest using blockchain on the construction site to improve logbooks' reliability and to monitor workers' performance and material balance in a more reliable way. They also suggest using blockchain in the maintenance phase when sensors are used to collect sensitive data and blockchain has the potential to store the data securely, thus improving data privacy. However, they don't see any use of blockchain in the initial phases, when architectural design and Bill of Materials are created.

Other potential applications of blockchain in construction engineering management suggested in [20] are: notarization-related applications to eliminate the verification time of documents' authenticity, transaction-related applications to facilitate automated procurement and payment, and provenance-related applications to improve the transparency and traceability of construction supply chains.

More potential applications of blockchain in the preconstruction stage, where the use of BIM is at its maximum, are suggested in [21]. Blockchain can enhance stakeholder confidence by enabling change tracking, establishing clear liabilities, providing visual evidence of information ownership, and reducing disputes over information authenticity. A distributed database avoids concentration of ownership and eliminates misuse and corruption of information, making it suitable for legal proofs.

During the design phase, any information exchange could be managed using blockchain to ensure that consensus is reached among all stakeholders. During the construction phase, invoicing and payments could be managed by blockchain-verified transactions. During operation, blockchain can be used to ensure that data collected by IoT sensors are validated and reliable, making, that is, HVAC installers and contractors accountable for sustainability targets declared during the design phase.

Blockchain is a technology that can help reduce confusion and the resulting litigation between a large number of parties involved in engineering projects. Blockchain may be part of the automation process, helping people make more things, better things, with less effort; more and better in terms of increasing efficiency, performance, quality, and innovation; and less in terms of time, resources, and negative impacts (e.g., social, environmental).

5. The major implementation challenges

The main disadvantages of the blockchain identified in [15] are: the high energy consumption, due to high demand for computing power used for the calculation process, and the balance between the number of nodes and the favorable user costs.

The key advantages of blockchain identified in [22] include decentralization, persistency, non-repudiation, anonymity, and auditability. Some of the most common vulnerabilities are end point vulnerabilities, public and private key security, blockchain integration platforms, untested at full scale, lack of standards and regulation, and untested code and vulnerabilities on smart contracts.

Turk and Klinc [19] observed that BIM files are usually huge, making the implementation of blockchain too demanding. They suggest that proper position for the integration of blockchain could be between the transaction-processing component

of the BIM server and its storage functionality, adding signed fingerprints to any information interchange. The biggest advantage blockchain technology provides is in using smart contracts to negotiate editing privileges and storing an immutable public record of all modifications to the model [20].

6. CAD data integrity

6.1 Information security

Information security consists of three components: confidentiality, integrity, and accessibility. Confidentiality protects against unauthorized disclosure of information. Integrity involves protection from unauthorized modifications of data—preventing adding, deleting, or changing the stored digital records. Availability means that data are fully available to authorized users when needed.

The integrity of the information means that the user's data cannot be changed without permission or that the information must be correct and complete. Confidential information must be protected from unauthorized changes, especially in a system such as financial institutions, health-care institutions, energy systems, etc., because the intentional or unintentional ordering of integrity can have catastrophic consequences. Preserving the integrity of information ensures this accuracy and correctness. The most important aspect of maintaining integrity is user authentication or identity verification to ensure that only authorized people can modify data in the system. The information must not be changed by accident or by the mistake of the user or the system. When handling confidential information, it is necessary to provide a strictly confidential environment that reduces the possibility of both intentional and accidental changes.

6.2 Data integrity threats

Trust is the key feature of blockchain technology [20]. If the construction activities are supported by the blockchain system, participants rely on blockchain to establish the trust relationship. Also, blockchain technology makes every participant a custodian of all the information flowing through the project's life cycle. Thus, blockchain creates an opportunity from the vulnerability; although the information is public, distributed, and unprotected, the traceability provided by blockchain ensures that any information stored in a blockchain is safe and cannot be altered.

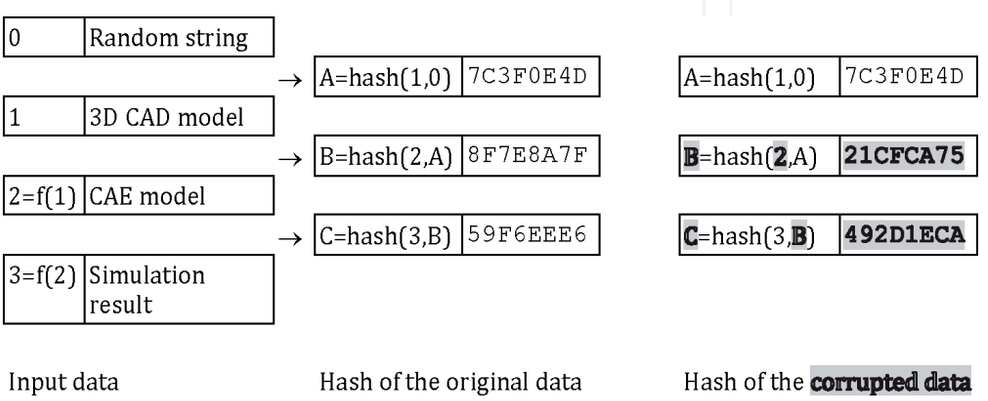


Figure 8.
Any change in a single blockchain step is traceable in a final digest [1].

Figure 8 shows how blockchain can be implemented in an engineering environment consisting of 3D CAD modeling and computer simulation (i.e., static structural analysis). A random string "0" serves as a cryptographic public key and is used to confirm the authenticity of the final output. The CAD model "1" is combined with a random string "0," and transformed into a fixed-size hash—block "A," using a common hash algorithm (i.e., MD5). CAE model "2" is a mathematical representation of a CAD model "1" accompanied by the material properties, constraints, forces, finite element mesh, and solver options. It is combined with hashed signature of the block "A" from the previous step and transformed to create the block "B." After the simulation is performed, the simulation result "3" is combined with the hashed signature of the block "B" from the previous step and transformed to create the block "C."

In case that any of the data in any step are corrupted or altered by an unauthorized team member, the changes are reflected to the blocks which were created after that step. If, for example, someone changed the material properties for the CAE model "2," block "A" is unchanged, but blocks "B" and "C" become completely different, revealing that data alteration occurred in the CAE model "2." As no changes occurred in the block "A," the process owner knows that 3D CAD geometry was not changed. In this example, the data integrity is provided through the identification of changes in the final digest "C," and data traceability means that blockchain reveals the source of data alteration in the CAE model "2."

A similar process can be applied in any phase of product's lifetime—information about the material properties of any element of the construction can be traced by blockchain along the entire supply chain [23]. This could prevent accidents caused by fire, earthquake, flooding, and other natural disasters, as weak spots cannot be hidden and the designers, suppliers, transporters, builders, and maintainers would easily be identified and traced for any flaw in the process. Being aware that information is transparent, they would surely do their best to provide the maximum quality of their performance. The product's owner would have high confidence in the quality, health, and safety standards applied. Procurement process would then be more transparent, yet keeping a certain amount of privacy, to provide fair market conditions, while enhancing the efficiency and trust within the entire supply chain.

7. Blockchain in mixed reality

Mixed reality (MR) combines physical and digital data by visually and interactively mixing digital graphical objects into the real environment in real time. Computers are used to generate 3D graphical objects, to map and integrate them into the real-world environment, and to represent their combination in computer displays.

Mixed reality is based on augmented reality (AR) [24], which is interactive, processed in real time, registered in three dimensions, and combines real with virtual space. Enabled by the progress and development in computer graphics hardware and software, MR can be one of the building blocks of cyber-physical manufacturing and Industry 4.0. The mixed reality concept relies on heavy data interchange between humans, environment, and computers. BIM and PDM/PLM also connect the physical built environment and its digital "shadow," stored in a dedicated database. In the design phase, MR can be used to visually represent the 3D CAD models or their simulated variations (i.e., structures deformed under the load) blended with the existing physical environment. It can also be used to assist the manufacturing, assembling, repairing, and maintaining of complex machinery.

Instead of using printed labels for machine or building parts, which can be altered, destroyed, or removed, MR can "project" the labels containing metadata about the products directly on the AR display (**Figure 9**). The labels thus become dynamic as they are connected to the database, acting similarly to a widely used face recognition software. Label data alteration can be protected by a blockchain.

Collaborative CAD is a digital representation of the entire engineering process. This process is vulnerable to attacks and errors and requires a lot of paper transactions and integrity checks to build trust between the stakeholders. Smart contracts are a digital implementation of trust-building components. Each step in the process is subjected to time-consuming and redundant checks before a relationship is established, and blockchain thus makes every decision logged and traceable, and, most importantly, irreversible and change-proof. This makes the entire BIM system highly reliable, open, yet confidential, eliminating any disputes between the process participants.

As all steps in the product's lifetime are tracked and stored in a blockchain, and a combined source of trust is being built among the stakeholders. **Figure 10**

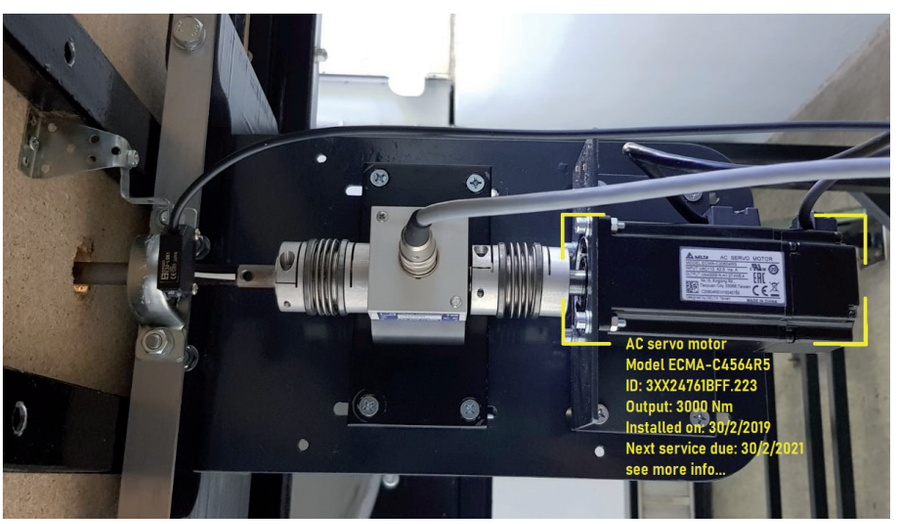


Figure 9.
Dynamic labeling of components utilizing MR.

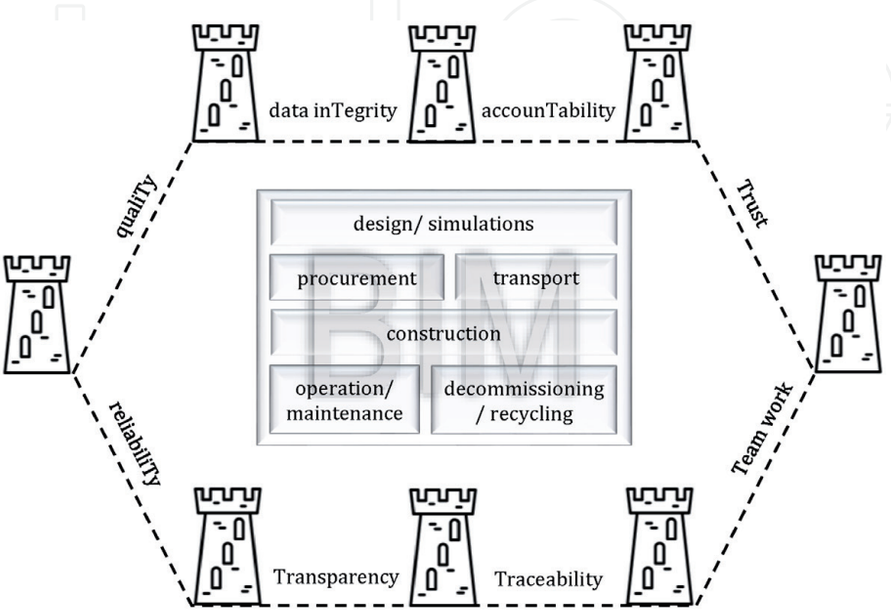


Figure 10.
Blockchain builds a fortress of Ts around BIM.

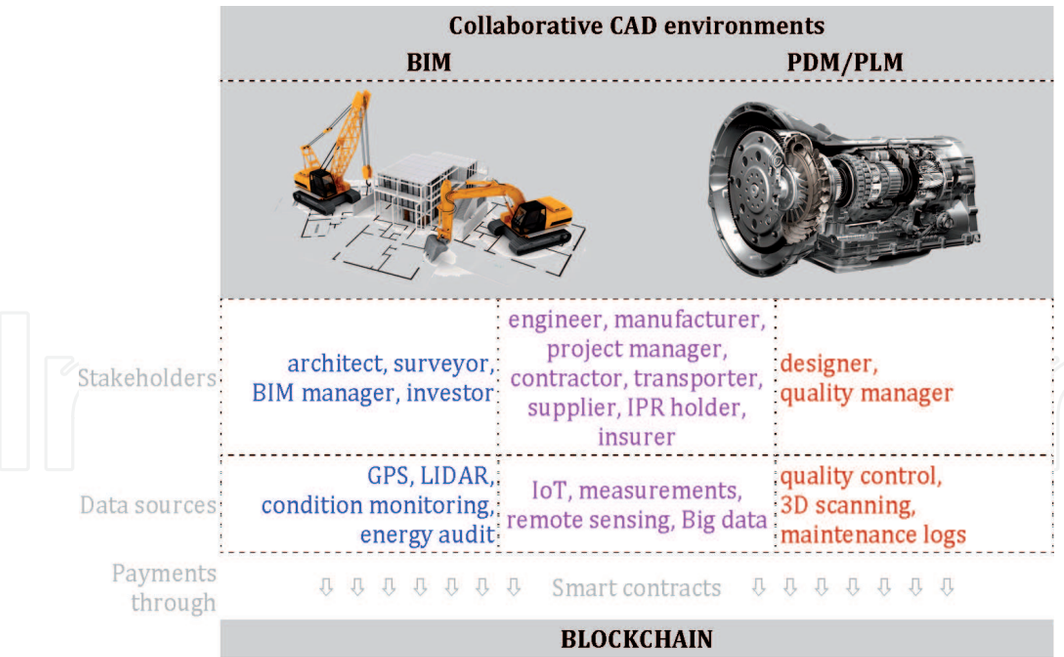


Figure 11.
The operation model of blockchain-enabled collaborative CAD.

illustrates how blockchain fortifies the BIM process by building sort of a fortress of terms containing letter "T": fortified data integrity, immutable accountability, mutual trust between stakeholders, improved teamwork, traceability of all information, transparency of all transactions, improved reliability, and high overall quality.

Figure 11, modified from the model presented in [23], describes the operation model of two similar blockchain-enabled collaborative CAD environments: BIM for the construction and civil engineering and PDM/PLM for mechanical engineering. Some stakeholders and data sources are present in both environments, and some are application-specific. All payment transactions are performed through smart contracts stored in a blockchain, which occur only when both parties involved in transaction mutually agree that conditions are all met (quality of service, time of delivery, and agreed prices are satisfactory for both sides).

Interoperability between different software components of BIM or PDM/PLM can be provided through a set of APIs (application programming interfaces).

8. Conclusion

Despite the great potential of blockchain technology in a collaborative CAD environment, the advantages of this technology are still in an early adoption stage in the BIM/PDM/PLM market. As blockchain eliminates any possibility of fraud, it increases mutual trust between the designers, contractors, suppliers, and surveyors. Payment transactions can be automated and the data from any step in the process is completely traceable and protected from unauthorized changes, making the process strong and resilient.

Other sectors already recognized the advantages of blockchain, especially the financial and supply chain services. It is questionable how much financial and banking sector belongs to mixed reality, as the nature of currencies is more digital than natural, especially when it comes to strictly digital cryptocurrencies. Supply chain, on the other side, is the genuine example of mixed reality, where physical goods are purchased, transported, and delivered, and the entire process is

supported by digital services such as eCommerce, eProcurement, GPS tracking, and eBanking. They both utilize the advantages of blockchain to make the process more efficient.

The disadvantages, such as the transparency of data and the slowness of storing data in the blockchain, are not key factors in delaying this technology implementation. The collaborative CAD can easily afford delays in a scale of minutes or hours, and they do not need real-time data. The transparency would be a problem when the intellectual property rights are threatened to be jeopardized, but blockchain keeps track of all transactions and any breach of copyright can be easily tracked and identified, even accompanied by the automated monetary transaction.

Another disadvantage is the high cost of blockchain maintenance, as block verification demands a significant amount of computing power, thus spending a lot of energy. Quantum computing could be one of the possible solutions for this computing resource demand.

Blockchain for collaborative CAD is still available only as an add-on technology provided by small vendors, while leading CAD software providers hesitate, either due to lack of awareness or just due to an opportunistic attitude.

Increasing demand by the Industry 4.0, Cyber-Physical Systems, IoT, Smart Cities, and other initiatives could foster the change in their approach to use the best what blockchain has to offer: data integrity, reliability, and traceability.

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Conflict of interest

The author declares that there is no conflict of interest.

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