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Evaluation of different typologies of Common Data Environment

From a physical server to the blockchain technology and IPFS.

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Summary

BIM is leading the construction towards a more digital, resilient and sustainable sector. A pillar, introduced by standards, to sustain the collaborative BIM environment is the Common Data Environment, which consists of centralized storage where all the information are gathered, shared and managed. Many different IT solutions can be adopted for different typologies of CDE. Project Server, Extranet, File-Based Retrieval System, Cloud-Storage and more innovative integration of Blockchain and IPFS. Most of them present drawbacks and benefits from their implementation. This study aims to clarify their characteristics and compare them to provide the sector with a clearer view of the different typologies of CDE. Most of the centralized CDE present issues related to data security, trustiness, accessibility of information and some of the cloud-storage commercial platforms shows problems of interoperability. While DCDE aims to solve all previously mentioned issues and increase the level of collaboration and trustiness throughout the process, guaranteeing, at the same time immutable data records and storage of the BIM model throughout all the stages of the construction process. Nevertheless, further implementations need to be carried out. Moreover, in this study, practical implementation tips are provided and a trivial example of DCDE is done.

Acknowledgements

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List of acronyms and abbreviations

AEC Architecture, Engineering Construction

AIM Asset Information Model

AR Augmented Reality

BIM Building Information Modelling

CAD Computer-Aided Design

CDE Common Data Environment

CID Content Identifier

DCDE Decentralized Common Data Environment

HLF Hyperledger Fabric

IFC Industry Foundation Classes

IPFS InterPlanetary File System

MSP Membership Service Provider

PIM Project Information Model

VR Virtual Reality

WIP Work in Progress

Part I

Prima Parte

Chapter 1

Introduction

The construction industry was often described as conservative and reluctant to change, not able to adapt to the external environment's requirements, which is crucial to do to guarantee survival and a competitive advantage in the market. These requirements are represented by, for example, incremental use of collaborative procedures to bear the workflow and inter-organizational integration, innovation and learning Gustavsson [2018].

Froese et al. Froese et al. [2007] revised companies that develop information technology (IT) for the construction industry in Canada. According to them, the most significant obstacle for construction IT development is related to the acceptance of new technologies by the industry. Additionally, Tapscott and Williams Tapscott and Williams [2010] mentioned that the key to a successful business in the 21st century is "collaboration". To prevail with competitors and continue to operate in the market, most of the firms must adapt to changes and modify their business strategy, focusing on the adoption of new technologies and promoting a collaborative environment.

In the last years, Building Information Modellings (BIMs) assumed a central role in directing the Construction Sector towards a more digital, resilient and sustainable sector. BIM is essentially a way to share and organize information in a structured way, simplifying, as a consequence, the complicated tasks arising during a construction project. BIM became the opening of the digital revolution, allowing a more collaborative and jointed design. Due to the relevance that it gained, standards have been developed to regulate, standardize and manage homogenously the BIM BCA [2013], ISO [2018] and BSI [2013]. Therefore, the standards identify the specification for information management, including the management roles, the path, the asset to use to maximize the BIM benefits and make the workflow compliant between the whole sector. A critical tool, introduced by the standards, necessary to bear a collaborative BIM environment, is the Common Data Environments (CDEs).

The CDE represent a digital central data repository where all the information and data are stored, gathered, managed and spread. All the data, information, models, documents and all relevant files of the project are stored within this central data repository. Various alternatives of systems, platforms and technology can be used to implement the CDE. One of the first solution adopted is the project server, but drawbacks related to scalability, security and costs arose. Therefore, others technologies based on cloud computing have been considered and, nowadays, widely utilized in the industry. Also thanks to the help of providers who developed various software with the functionality required by the CDE. Nevertheless, the cloud-based platform still preserves critical defects and difficulties to coordinate and boost the level of trustness in the sector. The main issue is related to their centralized structure, implying concerns in terms of data security and manipulation and denied information access Tao et al. [2021]. Making them not reliable in the long term and influencing negatively the output of the construction project. Therefore, limiting the benefits of BIM in the construction project, since the problems of security turn into issues of shareability and accessibility, critical concept to guarantee the collaboration.

A further step in terms of technology is needed since existing platforms and technology failed to meet the expectations. Therefore, a more secure, reliable and permanent storage technology needs to be employed. In recent years, blockchain gained a lot of interest due to the prosperity of cryptocurrencies in the financial sector. Nevertheless, blockchain started to spread in different sectors like Healthcare, education, Business and Government becoming widely usedNawari N. O. [2019] and a great source of cash flow due to the increase of efficiency of the process.

Blockchain is a distributed ledger technology, that guarantees an immutable and secure record of transactions. It consists of a sequential series of transactions recorded irreversibly into the blocks, founded upon the concept of transparency, authenticity and trust.

Several studies have been carried out about the opening of the construction sector towards Blockchain. Focusing principally on BIM, Supply chain, Life Cycle Operations, Smart cities, Intelligent Systems, Energy solutions and Decentralized Organisations Scott et al. [2021]. Recently, blockchain have started to be investigated as possible distributed storage systems for construction projects. Nevertheless, blockchain can not store a big amount of data within its chain making it unreliable for BIM models. Therefore, another technology must be introduced and adapted to have a data repository for BIM information, data and models. InterPlanetary File Systems (IPFSs) is a distributed file storage system, that allows storing the files in a distributed way throughout the network.

In the thesis, an evaluation of the principal typology of CDE is performed, trying to assess the main benefits and drawbacks in each of those. Moreover, a comparison to allow an accurate evaluation of the different platforms is provided. In order to allow the sector a clearer view of the different IT solutions that can be adopted. Furthermore, a practical guideline to the implementation of blockchain is provided trying to increase the study cases of it. The implementation is subdivided between companies with IT and non-IT knowledge.

Chapter 2

Background theory

2.1 Building Information Modelling (BIM)

During the last decades, the construction sector became much more complicated and with a considerable amount of factors to take into consideration like Project Management Factors or Human related Factors and so on Chan et al. [2004]. Therefore, the complex management led to a high-rate development of technological solutions to manage the complexity of the Architecture, Engineering Constructions (AECs) sector. The most famous and one of the most adopted IT solutions is BIMs. BIM is a process in which, all the actors involved in it, seek to collaborate by managing, sharing, and gathering information during the whole project life cycle of the building Lorek [2021].

The implementation of BIM can help the stakeholders to effectively share information and thereby reduce the time and the costs, enhance communication and coordination between the different teams and, additionally, improve the project quality Bryde et al. [2013]. Nevertheless, the US National BIM standard (2007) defined BIM not only as a process but, instead, consists of an umbrella term that includes other different dimensions. BIM can also be Building Information Model which consists of a digital representation of the object of the building, including a functional description of all its characteristics. Essentially, it can be defined as the product. Furthermore, Building Information Management includes all the operations and management of the design process performed through a digital-oriented information system.

One of the main problems associated with the construction sector is the huge impact that it has on the external environment. It has been assessed by several studies and research that the construction sector is considerably contributing, in all its procedures and operations on global CO_2 emission. For example, during the manufacturing process of concrete, the industry releases about 4% of the total CO_2 global emission deriving from non-combustion sources and an additional 4% deriving from the combustion process. So, in total, cement production accounts for roughly 8% of global CO_2 emissions Olivier et al. [2016] . Therefore, it is globally assessed how much polluting the construction sector is, and the complication that the industry delineates with respect to the environment. Consequently, it is crucial to pursue new methodology and especially new technology, like

BIM, that by capturing and sharing data provides information about what measures can be taken to decrease the impact of the construction sector.

Several research proved the benefits of BIM towards sustainability aspects. BIM is able to handle structured information, and thus, simplify all the complex tasks associated with the management of construction data. Through coordination, during the design, production and construction phase a more accurate and precise work is performed strongly reducing the waste and need for rework. Therefore, the introduction of BIM leads to a faster availability of design information and data, which consequently facilitates the decision-making process during the design stages. These aspects, contextualized with better collaboration, communication and with design optimization can trigger a not-negligible reduction of materials, energy and resources Wong and Fan [2013]. As a consequence, the amount of CO_2 will be reduced for the single project.

2.1.1 BIM maturity level

The British standard PAS 1992-2 BSI [2013] defined 3 different maturity levels of BIM application and use in the industry.

The maturity levels range from Level 0-3, and the PAS 1992 BSI [2013] defines the criteria required to belong to a specific stage. PAS 1992 explained graphically the different maturity levels, see picture below.

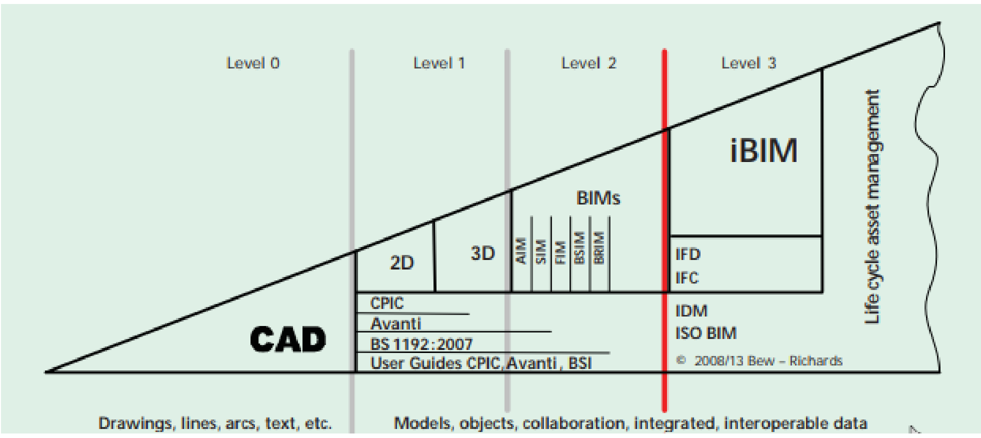

Figure 2.1. BIM Maturity Level BSI [2013]

BIM Level 0

This consists of an obsolete level in which all the information is unmanaged. They are obtained and spread through files or printouts of designs Computer-Aided Designs (CADs) in a paper or digital way of sharing. Moreover, models are vector and not object-based in this level.

BIM Level 1

In maturity level 1, there is a management of the CAD 2D and 3D drawings, through visualization and modelling of those. Nevertheless, in the level 1 BIM, models are not yet shared between the different stakeholders of the project establishing a very low collaboration and participation environment between the different actors. A raw version of CDE, defined as a central data repository is introduced in level 1. Nevertheless, the models are not yet inter-distributed among the stakeholders.

BIM Level 2

Level 2 BIM, principally, involves the use of a 3D CAD model with functional data and information incorporated. It is adequately shared, through an exchange of digital-based information, between the stakeholders. Consequently, defining a more collaborative environment as compared to Level 1.

However, Each team will work out a specific team related BIM model, meaning that for every time like Architects, Structural engineers one model will be uploaded. Since more distinct models are developed the whole project will be defined as, a federated model, where each team maintains the ownership and identity of the model. The online data repository, called CDE will characterize a core concept of the BIM level 2, reinforcing the collaboration among the stakeholders. Moreover, to enhance this central goal, an open and/or neutral format like Industry Foundation Classess (IFCs) should be used to increase interoperability and guarantee the exchange of files between different vendor-specific platforms.

BIM Level 3

The third level is denominated as 'iBIM' BSI [2013] which stands for "integrated BIM". It aspires to reach a full integration of the information in an online server repository. Level 3, introduce a high collaborative and integrated environment between all the different stakeholders, who can simultaneously work on the same model avoiding any kind of conflict. Therefore, Level 3 is based on an open data standard format like IFC, where all the data of the project are stored around one central storage United BIM. Moreover, to enhance interoperability open source BIM platform should be adopted to enhance the integration between the stakeholders.

Further BIM level

The HM Government developed in Digital Built Britain HM Government [2015] further maturity BIM level who takes into consideration different factors. UK government identified 4 different strategic development of the BIM Level 3:

- **BIM level 3A**: Enabling Improvements in the Level 2 Model.

  At this level, the aim is to improve the level 2 model by enhancing the exchange of data and information by improving the protocols and the process involved in the collaborative working environment.

- **BIM level 3B**: Enable new technologies and systems

  The aim is to incentive the development and integration of new technology and new system in order to create a more transparent, secure, reliable working environment based on paper-less exchanging information. Like for example AR or VR for the visualization and a better understanding of the model.

- **BIM level 3C**: Enable the development of new business models.

  The aim is to develop new business models like paperless contracts and new transactions methodology, integrated into commercial models.

- **BIM level 3D**: Become a world leader.

  At this level, the aim is to develop and integrate international contract models in BIM.

2.1.2 Interoperability

In the BIM environment, one of the key concepts is interoperability, which refers to the opportunity of exchanging files throughout the process without loss of data. The IEEE defined interoperability as the capability between two or more different systems to exchange information and be competent in handling the information received from the other system IEEE Computer Society [1990].

The implementation of interoperability is crucial in order to ensure a smooth workflow and integration between all the stakeholders within the project. All the different actors involved in the construction project, work on the project in different phases, with different software and computer applications. Each of them will transfer the information gathered towards the other team's members, in order to guarantee a high level of communication and integration between actors. Nevertheless, the software needs to be able to communicate with each other, by accessing the information and allowing the extraction, update and adaptation of data. Thus, interoperability is vital in order to maximize the efficiency of the design process and prevent the re-creation of data with a consequent waste of time and money Grilo and Jardim-Goncalves [2010].

Aware of the interoperability problems, many standards have been published in order to favor the exchange and readability of information between different software, consequently making the model compatible with each other De Gaetani et al. [2020]. To ensure compatibility the models need to be transferable and all the functional properties of the object need to be readable by the second software in the same way in which they were designed in the first one Grilo and Jardim-Goncalves [2010].

The BIM community tried to solve the problem of interoperability by introducing a new standardized format called IFCs. The format was developed by buildingSMART, which describes it as a standardized, digital representation of the built environment. They illustrate it as an open and internationally standardized file format that can adapt to different software platforms, hardware and devices permitting to manage several and different cases of application buildingSMART. Another critical aspect of interoperability as is underlined by Mirshokraei et al. Mirshokraei et al. [2019] in their research is the integration of BIM with other technologies like Augmented Realitys (ARs) and Virtual Realitys (VRs). It emphasizes the need of having compatible and communicating platforms, consequently implying the use of standardised formats like IFC. In order to quantify and qualify the efficiency of the interoperability, mainly three different factors need to be considered De Gaetani et al. [2020]:

- the action of translation of importing and exporting data between different applications
- the configuration of standardized file format
- the amount of data object that can be exchanged

Nevertheless, in the conclusion of their study De Gaetani et al. (2020) De Gaetani et al. [2020] underlined and assessed the importance of interoperability, since a good efficiency of it, can avoid the arise of issues between the stakeholders while running critical assignments within the project. Moreover, low efficiency of interoperability can lead to a loss of money, time and work hours for stakeholders throughout the project phases. The solutions to a lack of interoperability are either the manual transcription of data or debugging who can be frustrating and oppressive for those involved in the project.

2.2 Common Data Environment (CDE)

One of the pillar concepts of BIM is collaboration. During a construction project, several teams within different disciplines and with different backgrounds must cooperate. Therefore, a detailed plan of information management and meticulous communication procedures need to be drafted and supported by technical IT tools. Standards BSI [2013] and BCA [2013] developed the concept of a Common Data platform where all the actors can upload their files constituting a central storage and source of information called Common Data Environment. The CDE represent a digital place where all the information is stored, gathered, managed and spread. All the data, information, models, documents and all relevant files of the project are stored within the CDE, and thus, the CDE describes and preserve the whole BIM-design process Preidel et al. [2016].

An important benefit from the implementation of CDE is the prevention of information silos, which is the phenomenon whereby bad management of information limits and constraints transmission of information, reducing consequently, the collaboration and integration between all the stakeholders, thus, shading all the benefits introduced by BIM.

Bad management of information would lead to a chaotic and unstructured organization of data entailing an increase in project costs, a reduction in productivity, higher environmental impact and finally a not negligible waste of profit Radl and Kaiser [2019].

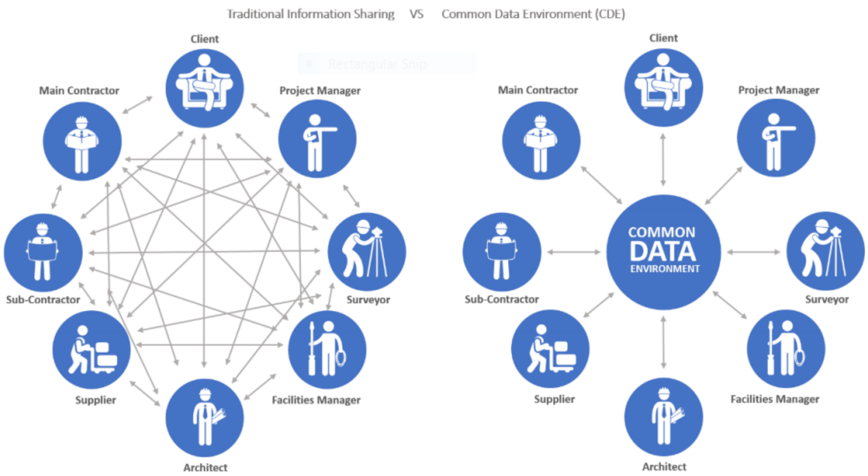

Figure 2.2. CDE core concept Source: Mordue [2018]

Another advantage of the implementation of is the transition from a chaotic, unstructured and paper-based environment to a structured, transparent, controllable and digitally-based source of information Richards [2010]. Hence, this promotes a trustworthy and collaborative environment between the parties and the actors involved in the design, construction and maintenance process, influencing not negligibly also productivity.

It is important to stress that CDE is not a solution to all evils and by implementing it the performances of the construction sector will not improve exponentially. CDE is a means, that facilitates a collaborative environment to distribute and provide access to all the information and data to all the actors involved, both vertically among the different roles and horizontally within the company. Nevertheless, coordination and integration will robustly improve the operations and performance of the construction sector.

Standards like PAS 1192 have developed a general framework and recommendations for the implementation of the CDE. Nevertheless, the guidelines are not strict leaving space for own interpretations and personal nuances Preidel et al. [2016]. In the next section, the PAS 1192 guidelines are described.

2.2.1 Workflow

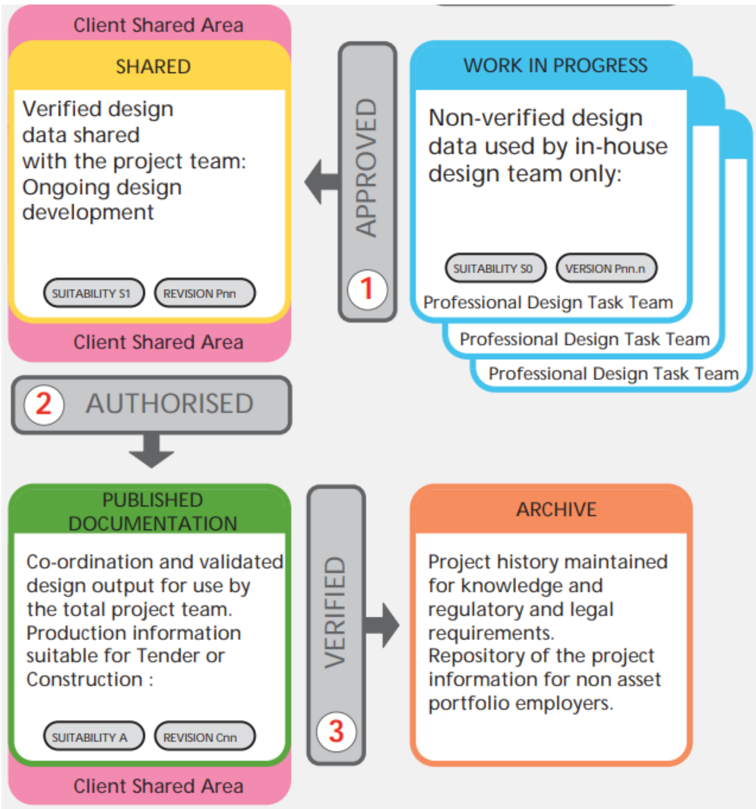

Figure 2.3. CDE workflow. Source:BSI [2013]

PAS 1992-2 BSI [2013] defined a logical framework in which the information should be managed and handled. It is composed of 4 different sections and 3 gates or sign-off procedures which allows the passage of information between different sections.

Functional Section	Description
WIP	Used to store unapproved information for each discipline within the competence team.
Shared	Approved and shared data with the others design team.
Published	In this section the model is published, validated, co-ordinated and used as a design output Mordue [2018].
Archived	In this section all documents, progress and transactions are recorded to provide a digital copy of the project life-cycle and administer disputes whether they arise.

Table 2.1. Functional section of CDE BSI [2013]

Work in progress

In this section, each member of the team carries out and develops his competence model that will be uploaded and stored in the central repository (CDE) Mordue [2018]. Moreover, the Work in Progresss (WIPs) section is not used to share information since it should be adopted to store unapproved information BSI [2013].

In this phase, access should be provided just to the team member of competence involved in the development of the model. Furthermore, a standardised and consistent way of naming files should be selected and maintained. PAS 1992-2 specified a status code to be adopted in the CDE. Finally, continuous review and assessment should be performed by the design teams to guarantee the quality of the information shared in the next sections Richards [2010].

Status code introduced by standards ISO [2018] and BSI [2013] indicates the position where the file is located within the CDE and what the information should be used for. The status code assigned during the WIP phase is:

- **S0**: initial status

Shared

After the model is checked, reviewed and approved it is able to pass Gate 1 and is ready to be integrated with all other models and information developed by each specific design team. Essentially, the model is checked assessed to be in harmony and compliant with other models without issues or clashes. In this phase, will be provided access and the possibility to comment to the other teams to get clarification or solve clashes.

The status code assigned during the Shared phase are:

- **S1**: suitable for coordination
- **S2**: suitable for information+

- **S3**: suitable for review and comment
- **S4**: suitable for stage approval
- **S5**: not in use
- **S6**: suitable for Project Information Model authorisation
- **S7**: suitable for Asset Information Model authorisation

Published documentation

Before transition through the "Approval Gate 2", the documentation is checked and approved and can then pass from Shared to the Published section. In this section, files will be judged by the clients who will assign to those a specific code Richards [2010]:

- **A**: Fit for construction
- **B**: Partially signed off/ Comments
- **C**: Rejected
- **D**: Need for revision by the design team, it means "approved but not authorized"

Archive

Constitute the final section of the workflow. In this area of the CDE all documents, progress and transactions are recorded to provide a digital copy of the project life-cycle and administer disputes whether they arise.

2.2.2 Roles

The clarification of the roles, authority, duties and responsibilities is a critical step in order to provide efficient information management. Before any operation is carried out the roles should be defined and assigned univocally, and all the parties should agree on it NWCH [2018]. Moreover, with the implementation of the CDE new roles are identified by PAS 1992-2 BSI [2013] that need to be implemented in order to guarantee an efficient information management. Moreover, the contact should be clearly stated in a table within the CDE to facilitate communication between parties.

Information management

They must be responsible for maintenance, acquisition and even rejection of information in the CDE and be able to guarantee a stable transmission of information. Finally, they must promote integration and coordination between CDE. Nevertheless, they do not have any design responsibility BSI [2013].

Project delivery management

They need to ensure the delivery of information exchanges and manage information transfer inside the CDE.

Lead designer

They need to lead the management of information approval. More specifically, they need to confirm and approve the status of information inside the CDE.

Task team manager

They are responsible of the design production of design output specific of relative team. Moreover, they are responsible of accepting, rejecting and mantaining information inside the CDE NWCH [2018].

Task information manager

They are responsible for confirming that the information is suitable for the CDE. They also need to direct the production of task information while referring and agreeing to standards.

Interface manager

They must manage the spatial coordination for the task team and come up with resolutions to the coordination of clashes between different task teams.

Information originator

Responsible for producing project outputs, of the ownership of the model. Finally, they need to develop some parts of the information model coherent with specific duties.

2.2.3 Data security

With the implementation of digital technology, the construction sector is slightly moving towards a digital built environment. The effect, in short, of this renovation, is a higher efficiency on the delivery and exchange of information and higher productivity. Nevertheless, the increased use of IT solutions in information management in the AEC sector implied, as a consequence, security and vulnerability issues on the leakage and access of the project information. Therefore, it becomes crucial to draft an executive plan on authorization and administer the vulnerable side of cyber and physical security as careful as possible. PAS 1192-5:2015 BSI [2015] identified the main security issues on which particular attention should be placed.

- **Hostile reconnaissance**. The employer should be aware of the technique in which hostile reconnaissance is done to prevent leakage of sensitive information.

- **Malicious acts**. It is related to the business risk deriving from a failure of IT technology that originates from a malicious attack due to external and internal threats.
- **Loss or disclosure of intellectual property.** Requirement in protecting and securing its own and others' intellectual property.
- **Loss or disclosure of commercially sensitive information.** Secure and protect all the commercially sensitive information that can be betrayed by commercial espionage, as a consequence the stakeholders could be damaged.
- **Release of personally identifiable information.**
- **Aggregation of data.** The employers must be aware of the risk deriving from the gathering and aggregation of data. It occurs in particular in centralized data storage, where all the data are collected in unique storage.

Nevertheless, it is crucial to quote the core concept of technological security since the cyber security of the construction sector must be arranged on those. Although, care must be taken even to the physical security of the system BSI [2015].

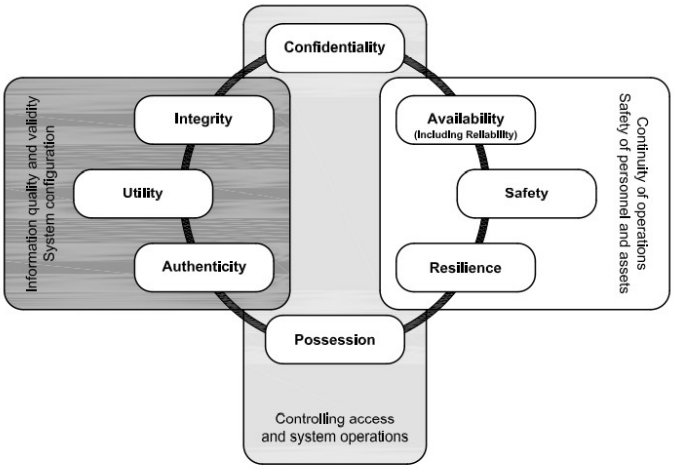

Figure 2.4. Cyber security core concept Source:BSI [2015]

- **Confidentiality**: it refers to the regulation and restriction of access to project information or data, preventing unauthorized access to confidential material.
- **Availability**: It refers to the need of guaranteeing constantly availability, usability and reliability of project data and information. Implicitly connected and related to the resilience of CDE.
- **Safety**: Project information and data must be used to guarantee safety during the whole project lifecycle. And prevent damage to things, people and the environment.

- **Resilience**: Characterize the toughness of the system, and its capability to recover quickly and arrange accordingly to the presence of a harmful internal and/or external factor.
- **Possession**: Possession of the built asset system in order to control and avoid unauthorized access with a consequent leakage and tampering of data.
- **Authenticity**: Ensure the correctness of the project data and guarantee that the digital built environment have not been manipulated or altered.
- **Utility**: it refers to the ability that data and information maintain their practical use throughout the project lifecycle.
- **Integrity**: ensures that data and information have not been tampered with and modified and therefore are coherent with the information system.

Moreover, the application of this concept can strongly influence the project lifecycle working environment in terms of trust and control Designing Buildings Wiki [2021]. Nevertheless, more technical standards and BIM protocols have been drafted to solve the issues of data ownership, data security and data authenticity like CIC [2018] and CPNI [2017].

2.3 Network architecture

Network architecture represent the framework to guaranty a seamless transfer of data and information between the nodes of the network. There are several different type of network architecture but the principal involved in this study are the following.

2.3.1 Centralized Network

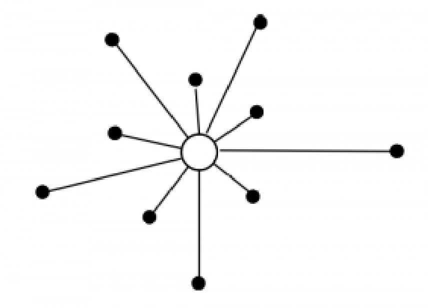

Figure 2.5. Centralized Network ZPE

Centralized network architecture is assembled around a unique, centralized server that administers and supervise all the data transactions between the single nodes of the networkZPE, N-able [2018] and Cryptopedia [2021].

The workflow of the centralized server links the client nodes to the principal server and manages all the data requests and responses. As a consequence, this architecture entails the presence of a single point of failure for the whole network structureCryptopedia [2021].

Nevertheless, the plurality of network architecture used nowadays on the web, reflect the centralized structure. For example, social media platforms, online bank accounts and so on are constituted by centralized network architecture.

Advantages

- **Quick and easy deployment** Centralized structure are very easy to deploy and manage in the initial stage, because only one configuration needs to be doneCryptopedia [2021] and ZPE.
- **Inexpensive** The cost of implementation is relative low, due to the low amount of servers used and moreover the maintenance is affordable making this architecture a cost-effective optionsCryptopedia [2021] and ZPE.
- **Consistency** Thanks to the top-down nature it will be easier to standardize interactions between users and the principal server leading to a higher coherence and consistency in the user experience Cryptopedia [2021].

Disadvantages

- **Security risks** Due to the centralization of the network, only one point of failure is present in the network, making it highly vulnerable to tampering and cybersecurity attacks Cryptopedia [2021].

- **Take down servers** The single point of failure implies a higher risk of having the server unusable in case of a bug, attack or even maintenance. Causing the interruption of all the services.

- **Scalability** It is rather complex to adapt the server after a certain limit is reached. It requires an adaptation in terms of storage, bandwidth and processing power. Moreover, when the traffic network increase, that can cause a bottleneck Cryptopedia [2021] and ZPE.

2.3.2 Decentralized Network

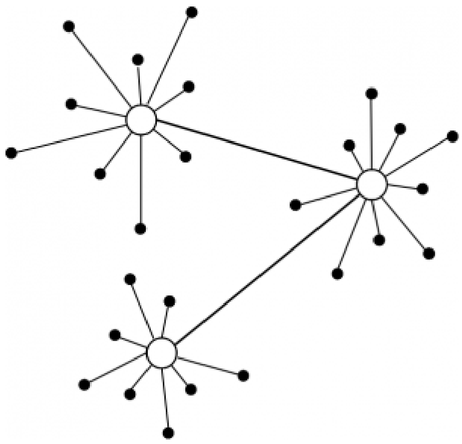

Figure 2.6. Decentralized Network ZPE

In a decentralized network architecture instead of relying on a unique centralized server, the workload is spread across multiple and distributed servers across the networks. Every distributed component will establish a client-server connection. Thus, if one server unit is taken down for maintenance or an external attack, the network does not face any interruption since the workload can be shifted to the other server units ZPE and Cryptopedia [2021].

Advantages

- **More scalable and flexible.** Improved flexibility is due to the absence of a centralized master server, so if one server goes down the others can substitute it temporarily. Moreover, a decentralized server facilitates the scale of the network since it is only necessary to add a supplementary master server to the network.

- **Better performances.** When the traffic grows decentralized servers do not suffer from bottlenecks, since they can split the traffic among the master servers and new master nodes can be created in the region where the traffic is high
- **Privacy.** Since the single point of failure is missing, there is less risk of leakage of data. Moreover, the information is distributed across the whole network complicating the tracking of information and consequently any malicious act.

Disadvantages

- **High installation and maintenance cost.** Decentralized networks architecture have higher fault tolerance, implying an increase in the cost of maintenance and installation since multiple servers need to be configured and maintained. Therefore, higher IT resources are required.
- **Coordination** Complex to manage the hierarchy of the nodes and consequently the regulation of each point of the system. Without coordination, an interruption or an error can cause relatively security issues in the network.
- **Security** Hackers can use the weak point of the network to access sensible information. These are the replication of the master server.

2.3.3 Distributed Network

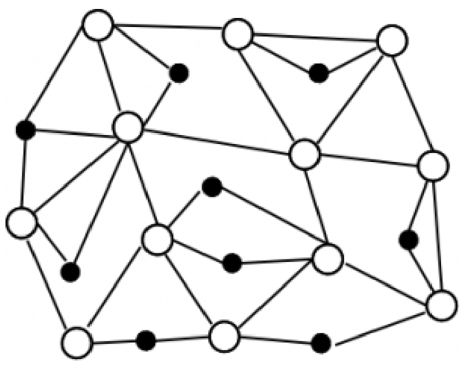

Figure 2.7. Distributed Network ZPE

In the distributed network architecture, the network is composed of a plurality of nodes that are evenly distributed across the whole network. Implying that, computational load and data are spread throughout the web and not in a specific master server. Therefore, data are available to all the users who can vote in order to change the state of the network. The decision-making process is seamlessly sustained by every node, leading to the consensus of the whole network.

Advantages

- **Extreme fault tolerance.** Distributed networks are geographically spread. Moreover, whether a node fails, all the other nodes will support the network by carrying an additional workload in order to recreate a balance and equity among the network.
- **High performances and scalability.** It is very easy to scale and rearrange a distributed network since simply more devices/nodes need to be added. Moreover, lower latency is usually shown since there is an even workload distribution in the network.
- **Transparency.** All the data are visible and distributed across the entire network. It makes it extremely difficult to tamper maliciously the data contained in the network. Additionally, cryptographic measures are adopted to increase the privacy and security of the network.
- **Privacy** Sensitive data are shared across the network, making the complex a malevolent leakage of sensitive data. If eventually, a hacker enters into the network, they can only obtain information contained in the individual node.

Disadvantages

- **High installation and maintenance cost.** Similar problem to a decentralized network, the high amount of nodes entails an increase in IT resources with a consequent increase in cost, both during installation and during maintenance.
- **Coordination.** It is difficult to achieve coordination when the hierarchy is absolutely missing.

Part II

Seconda Parte

Chapter 3

Discussion

PAS 1992 BSI [2015] defined the CDE as a unique source of information, which is used to store, gather, manage and spread all the relevant information of the project in a digital environment. The tool that allows the construction sector to ensure that different teams collaborate and work together on the same database is the CDE.

It was introduced by standards like PAS 1992 BSI [2015]and ISO 19650 ISO [2018] which aimed at introducing and boosting a common working and storage environment to facilitate the work of different team. Basically, it derived from the need of improving the collaboration among the stakeholders. In short, a CDE is defined as a centralized storage which contains all the projects-related information and promotes the collaboration between the actors since everyone can share and access to the most up-to-date information. The CDE can be labelled as a collaborative technology which aims at increase the openness and trustiness among the multiple actors involved in the construction project into a digital environment. Defined the scope, there are several technologies that can be adopted in order to provide a central data repository for a construction project. Nevertheless, it is worth mentioning that the introduction of a technology will not automatically imply an high level of collaboration, it can be an enabler, but collaboration is human activity that can not be achieved if humans are not prepared for it Wilkinson [2005].

Many technological solutions can be adopted to define a common data repository like for example a project server, an extranet, a file-based retrieval system, a cloud server or a distributed file storage system.

3.1 Project server

The project server is a informatic tool that elaborates and manage all the information on a network, and returns back the information to the clients who made the requests. A project server consists in a physical server that stores the data and information and can then share those to the users. It can generally be accessed through a Local Area Network (LAN) or a Wide Area Network (WAN). The requirements are related to the hardware and software that the server is equipped, in order to guarantee a certain storage space and processing speed Mordue [2018].

3.2 Extranet

Nowadays, the web is organized into three different macro areas. Internet, extranet and intranet. Internet is what is accessible by everyone, when we search for something on google, we are exploiting the World Wide Web. Intranet is the most closed web service, as the name suggests just a specific amount of people within an organization can access the information published into it. Intranet is a private network that exploits the same technology used on the internet. It is a protected and isolated environment towards the external since it could contain some sensible information of the company, it is managed through firewalls and restricted access. The extranet is similar to the intranet but it is less isolated and can be accessed by authorised people even if they are from different companies. Extranet consists of a private network that is shared by the companies with third partyZola [2021]. Intranet is the most protected and isolated component, it is included in the extranet which can be accessed transversally by different organizations, which is incorporated into the internet who is the widest and most general.

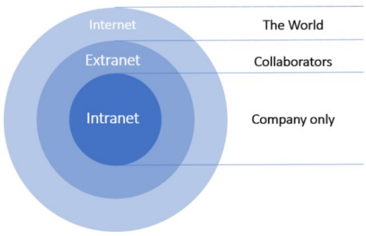

Figure 3.1. Web suddivision, source: Mordue [2018]

Nowadays, the web is organized into three different macro areas. Internet, extranet and intranet. Internet is what is accessible in the main use cases, the extranet is related to the possibility to share and exchange large volumes of data and information and work simultaneously on them with other companies. Moreover, the extranet allows sharing information and news solely with joint organizationsZola [2021].

Companies can adopt extranet as a central repository and let it constitute their CDE, it can be extended to all the organizations involved in the project. It consists of an extension of their intranet to all the actors working on the construction project. The requirements are an ID and a password to guarantee restricted access just to authorised people. When using an extranet, data will be stored in a centralised data storage system with limited access just to authorised people Mordue [2018].

3.3 File-based retrieval system

A file-based retrieval system consists of digital document storage associated with a data retrieval system Tallman. The data retrieval allows obtaining data from the digital database by using specific criteria and constraints that are set by a query. The retrieval system search for information that matches the criteria of the query, within the document of the database Mordue [2018].

3.4 Cloud storage

Cloud storage is a service provided by cloud computing which is a technology that allows exploiting the technological and informatics resources available on the internet, instead of accessing them on the computer's hard drive they are available remotely. Cloud storage enables the clients to store the data, not directly on your hardware, rather, it saves those on a remote location accessible at any moment through a public or private network connection. Therefore, the provider stores, maintains, handles, backs up remotely and holds the data uploaded into it in exchange for a contribution IBM Cloud Education [2019].

Cloud storage is highly adaptable and has several interesting features that should be investigated deeper. Furthermore, cloud storage fits BIM and Common data Environment needs, being able to solve its main issues France [2010].

Cloud storage can increase the horizon within the project is carried out, enabling cross-company interactions and collaboration between the stakeholders, enhancing the accessibility and usability of the information. Thus, improving the efficiency of information communication. All the stakeholders can access the file directly on the cloud platform without the need of downloading and then reupload it into the server. Allowing all the actors to work and cooperate on a real-time shared model Ding and Xu [2014]. Financially speaking, clouds storage is cheaper than physically-based storage systems resources Wu et al. [2010]. The most famous cloud storage provide with their related service are Google Drive, Dropbox, OneDrive and so on, which are relatively cheap reducing the need for investments for internal storage resources, maintenance and management reducing the cost of BIM implementation Ding and Xu [2014]. Nevertheless, the most technical cloud storage systems, those designed for specific business purposes, result to be quite expensive. Moreover, cloud storage is scalable and expansible. Whether the space available is not necessary no physical operations need to be carried out, but it is just necessary to upgrade the plan to get the extra space needed. In the BIM context, this allows overcoming the overload storage problem, allowing the construction companies to adapt their plan to the space needed without investing in physical expensive servers Ding and Xu [2014].

A portion of research related to CDE focused on the development of a cloud-based data environment. For example, Liu et al. Liu et al. [2014] defined the framework to develop a cloud-based data-hub environment to store and update the BIM models. Thus, to improve the management process of information and update seamlessly changing BIM models. These IT solutions would improve the BIM management process by automating the procedure, better collecting the information and finally, better coordinating the stakeholders. Logothetis et al. Logothetis et al. [2018] in their study drafted and proposed a framework of open-source Cloud-based systems for storing, analysing, assessing and reviewing BIM models. The openness of the cloud-based central repository system constitutes a key factor. Many platforms, nowadays, developed by a provider are strongly restricted and constrained to that complementary software provided by the same provider, thus, limiting accessibility, usability, management, reliability and interoperability of the digital data.

3.4.1 Autodesk BIM360

Autodesk BIM360 is solution developed by the Autodesk Group. It consists of a centralized cloud-storage system where all the data and information are accessible by all the authorized project participants from any location and in real-time. One of the main

Figure 3.2. Autodesk BIM360 logo

characteristics of BIM 360 is centralized document management who allows sharing and distributing the files through structured document maintenance and storage. Ensuring that the document is accessed by those who have the authorization. Moreover, BIM360 improves model coordination minimizing the rework that needs to be done during the lifecycle of the project Autodesk. Furthermore, BIM360 has more features compared to the services from other providers, due to the added cloud computing capabilities and not characterized only by a software design with only software features. Chong et al. [2014a].

3.4.2 Trimble connect

Trimble Connect is a project collaboration platform, cloud-based, provided by Tekla structures. The platform allows all the project participants to share in real-time all the project data and information, that will be available on the program Harpaceas. Trimble Connect

Figure 3.3. Trimble Connect logo

is therefore a central-cloud repository for the management and storage of the most recent and up-to-date information and data related to the project. Moreover, Trimble connect is defined by an interoperability characteristic, since it can directly be connected to different softwares like Revit, Sketch Up and Tekla structures. In addition, it is possible to visualize the BIM model directly from Trimble connect without the need of using and open several third-party applications and BIM models. The presence of a unique and centralized repository system increases the efficiency of the teams by facilitating collaboration between those Trimble.

3.4.3 BIM Cloud

BIM cloud is the collaboration platform developed and provided by Graphisoft. It is a cloud platform that exploits Google cloud and Google servers spread throughout the world. Likewise previous platforms, this central Data Repository BIM clouds guarantees real-time and secure collaboration among the stakeholders. It enables the communication between Archicad and BIMx, facilitating the operation of those using that software.

Figure 3.4. BIM cloud logo

3.4.4 Drawnbacks of clouds storage

Many studies have shown that the existing commercial BIM platforms can not ensure and support the collaboration among the stakeholders in the multidisciplinary field in which they operate Shen et al. [2010], failing therefore in one the principal scope for which they are implemented. Moreover, they principally provide a service about the storage of data of the construction process without integrating it with different functionalities like scheduling data, the workflow, costs, maintenance information and manufacturers details Argiolas et al. [2016]. Chong et al Chong et al. [2014b] reviewed 6 of the most common cloud-based BIM platform like Autodesk BIM 360 and discovered that only three of these commercial platforms enable a private cloud and only two of them can recognise IFC files, strongly restricting interoperability and thus, collaboration.

Most of the BIM commercial design platforms and Common Data Environment are, nowadays, based on a centralized architecture of the network. Indeed, cloud platforms and databases, like BIM platforms, are highly vulnerable to cyber-attacks being very sensitive to data loss, data access and control of data Studnia et al. [2012]. Entailing a significant deficiency of those in terms of cybersecurity, related to design data manipulation and denial data access Argiolas et al. [2016]. The abovementioned drawbacks would strongly influence the workflow and process arising during the construction projects. Most of the time, project participants do not trust each other, and therefore they do not tend to trust a fallible centralized database environment where all the documents are stored and managed Das et al. [2021].

Parn et al.Pärn and Edwards [2019] evaluated in their study the principal cyber threats into a CDE. Stating that data manipulation has a deep repercussion throughout the project lifecycle impacting data traceability and reliability. Moreover, the tampering of data into a central data repository is arduous to discover leading to a loss or irreversible damage of data Aljarman et al. [2020].

Boyes et al. Boyes [2014] identified and investigated the main threats that affect CDE and the connected systems. External threats agents are related to all those malicious extraneous to the projects which aim to tamper the documents and data of the project. However, some security defences protocols have been approved from external threats like antivirus, access control and firewalls Argiolas et al. [2016].

Cyber security threats are internal threat agents, all those individuals within the construction project. Internal threat agents can be subsequently divided into two categories. A malicious insider who aims to steal, tamper or leak sensitive data abusing its authorised access. A non-malicious insider who could unconsciously cause corruption, or a loss of BIM data and project information due to an error, an omission or negligence. Although security defences are introduced for external threats, they are not sufficient to mitigate and block an insider attack. Finally, the last cyber security threats are related to system and business failures, which may result from different and various causes. Natural causes like weather, animal or insect may lead to a failure of the systems storing the BIM model. A system failure, like a corruption of the system, may cause a loss of BIM data and information. Lastly, a business failure may deny the possibility to access the BIM data. Normally, a third vendor party provide the platform storing all the BIM data either them or a member will have the complete control and authority of BIM data implying a risk of denial access in the case of server breakdown Tao et al. [2021] or whether the administrator due to a controversial, decide to not provide the access Elliott.

According to Bakis et al. Bakis et al. [2007], "in the construction industry, the use of a single central repository to store the design information is not usually a viable option due to the fragmented nature and adversarial behaviour that characterizes the industry". Therefore, it seems necessary to develop and introduce new emerging technologies that enable a Decentralized Common Data Environment, solving the main issues associated with the centralized CDE.

3.5 Distributed file storage system

Centralized Common Data Environment presents some vulnerabilities and issues in terms of cybersecurity, moreover, as Bakis stated Bakis et al. [2007] a central data repository is not suitable due to the branched structure and the low level of trust among the participants in the construction sector. It is, therefore, crucial to evaluate alternatives and a new way of organizing the information and data within a construction project.

Blockchain, as underlined in the previous chapter, is a distributed peer-to-peer system architecture network that enables all the peers of the network to access the complete blockchain network, with all the information contained in it. Blockchain ensures that data contained in the chain will be secure, immutable, unchangeable, and traceable in the distributed network. It is evident, therefore, how blockchain technology is complementary to the need of a CDE in the construction sector. Literature investigated the potential benefits of employing the blockchain technology in the construction sector and BIM processes, discovering the potential of an increased collaborative environment and level of trust due to data records Tao et al. [2021], the possibility to reuse BIM data Liu et al. [2019], to guarantee the traceability and ownership of the data Xue and Lu [2020], support the decision-making process and accelerate it Nawari and Ravindran [2019] and finally remove third-vendor provider Turk and Klinc [2017].

Blockchain is, thus, a great coupling with the BIM-data and CDE, nevertheless, blockchain is not designed to store a large amount of data in a single block, like BIM model files since the amount of data storable in a block is limited. The largest amount of data that a block can store is a defined block size limit, for example, in the case of Bitcoin the block size limit is 1MB, making it inadequate for storage of BIM or CAD files Bitstamp [2021].

It is, therefore, necessary to introduce a new technology which allows to store large-sized data in a distributed way. Many solutions have been developed in the recent days, like BigChain Data, Filecoin and InterPlanetary File System. InterPlanetary File System is a peer-to-peer file storage system that allows the storage of large-sized files like BIM and CAD files. And it is reasonable to believe that both technologies can be complementary in the formation of a Distributed Common Data Environment as Tao et. al. have defined Tao et al. [2021]. IPFS return a unique cryptographic hash, every time a file is uploaded, which identifies permanently and invariably the document in the network. Thus, the integration of IPFS into blockchain workflow overcome the storage issue, unlocking the possibility to develop a secure, high collaborative, and trustworthy Common Data Environment.

Framework

In their study Tao et al. Tao et al. [2021] developed a framework for a DCDE with the integration of blockchain and IPFS. Nevertheless, since the framework is shaped around a CDE which is homogenized by standards, the original CDE structure will be maintained. Therefore, in the WIP just members within the respective team will have access to the blockchain of the specific team without sharing it with the rest of the stakeholders. However, in the shared section all the models will be merged and checked that are compliant with each other, solving all the issues and clashes that arise. Therefore, it is crucial in this section to have a shared a common environment between the design team, including and entailing a unique blockchain that all the authorised stakeholders can access and assess. Moreover, due to the structure of IPFS, every time a file is downloaded the peer becomes a provider of the file. Enforcing furtherly the shared structure of the CDE. In the third section, the documents will be published widening the access to the blockchain, for example, the constructor. Finally, in the last section, Archive, due to the immutability of blockchain a permanent records of data will be maintained including all the workflow of the construction design process, that will be accessible whether data and information want to be reused or whether problems arise and old information needs to be assessed.

1. **Upload the file into the IPFS network which will return the CID.** In the figure below the user interface of the IPFS desktop application is present, a member of the design team will upload the BIM model into the IPFS network which will return the CID of the file.

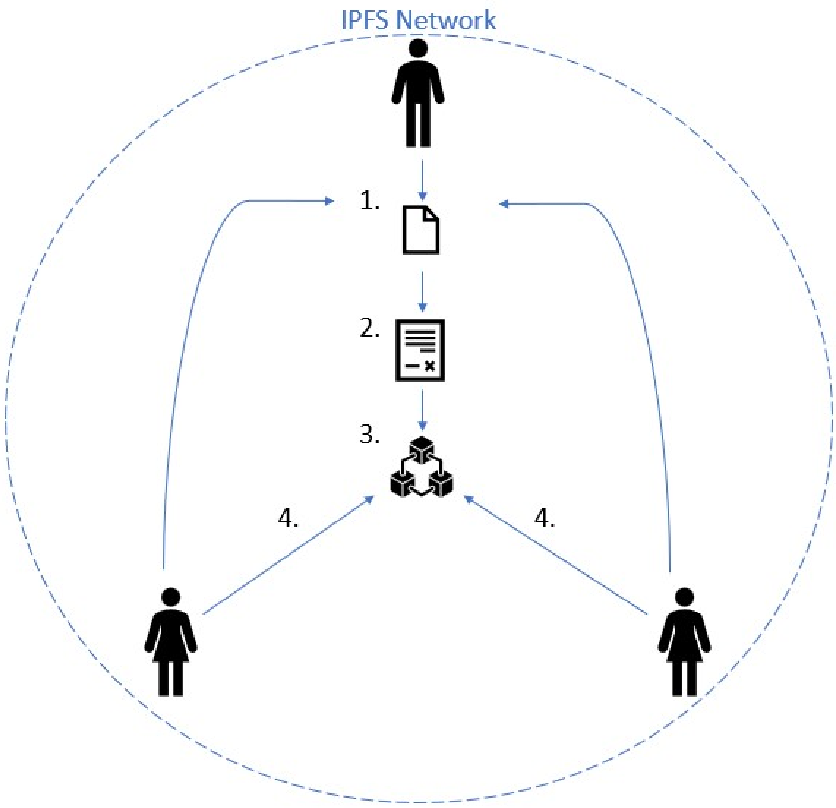

Figure 3.5. Blockchain and IPFS integration framework Adapted by: Tao et al. [2021]

2. **Upload the transaction into the blockchain network.** Through a smart contract, the critical information of the file, who are summarised in Table 2 are uploaded into the blockchain network. The transaction will constitute a new block which will be mined to guarantee authenticity and then added to the chain which will be immediately synchronized to all the network, meaning all the authorized stakeholders. A figure of a blockchain example is available in the figure below, where all the information can be accessed and viewed through the blockchain.

3. **Accessing design file using CID.** Now, all the stakeholders who have access to the blockchain can see the new blocks with all the information contained in it, and can, therefore access and download the BIM model from IPFS through the CID. Entailing that they become another provider of the BIM model throughout the IPFS network. For example, the structural engineers can access the model published by the architectural team, they can download it and check the clashes.

4. **Repeat the previous steps to form the blockchain.** After downloading and evaluating the BIM model the stakeholders can coordinate with the other design

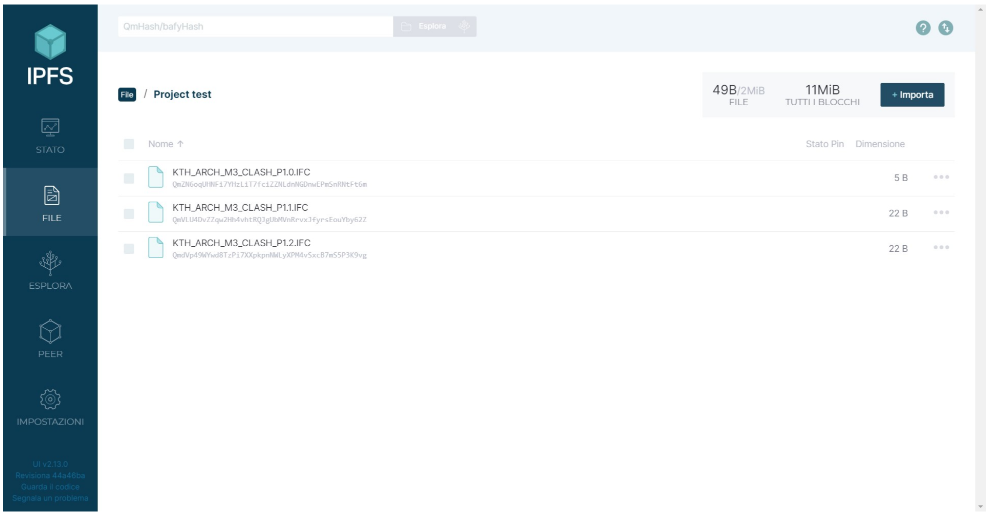

Figure 3.6. IPFS User Interface

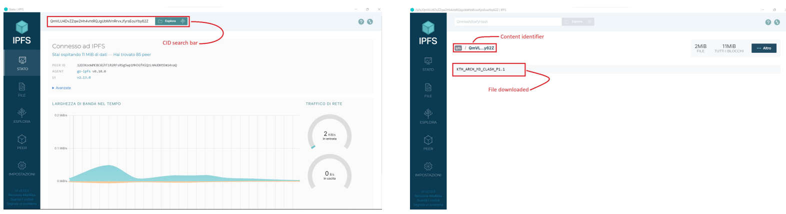

Figure 3.7. Ipfs interface

team by publishing a new file, with the same procedure of steps 1-3, and complete the file until a high-quality standard is achieved. This led to the formation of a series of updated BIM files that will be all contained within the blockchain, as the figure below indicates. Therefore, immutable data records of all the adjustments, the authors, the data and critical information are stored permanently and securely within the blockchain.

Through the employment of the DCDE, where the framework is graphically represented in Figure 3.5, there are no problems anymore of access and access denial since, all the peers can access the file, all the peers have a complete record of transactions, each peer can become a provider of the file guaranteeing multiple sources of access to the file and finally, no central authority or central control of a single peer is present, since all the peers are equal in a blockchain network Tao et al. [2021]. Thus, encouraging a trustworthy environment.

Moreover, data are immutable and secure into DCDE since blockchain guarantees

Attributes	Attributes explanation	Block content
CID	Content Identifier of the file related.	QmZN6oqUHNFi7YHzLiT7 fciZ-ZNLdnNGDnwEPmSn RNtFt6m
ID	Indicates the name of the file based on standards like ISO [2018] and BSI [2013]	KTH_ARCH_M3
Version	Standards like ISO [2018] and BSI [2013] specifies the name to use to diversify the different versions of the file.	P02
Status code	Indicates what the information should be used for	S1
Owner	Owner of the file uploaded	ARCH
CID dependent file	In the case in which a file is dependent upon the another one, this section label the main file	—
From: to:	This section represents the team who is creating the file and the team who is receiving it.	-
Data	Timestamp of when the block is created	2022-01-05 15:23:16
Hash	The hash is obtained through cryptography, it consists is the string that identifies the block in the chain	000286b501fdaa32dae75dc037 935bcd455e9b6d8045e6ff70df 03d324b4cfda

Table 3.1. Example of block in DCDE

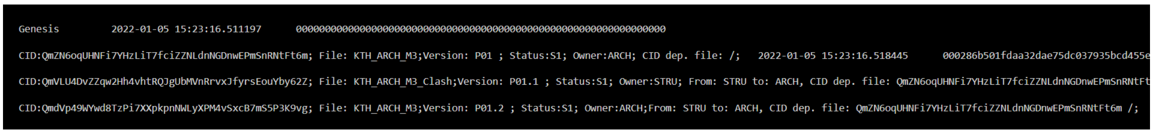

Figure 3.8. Blockchain

traceable and unmodifiable data records and IPFS ensures reliability of data since whether the data are changed even the CID is modified as a consequence.

3.5.1 Practical implementation

The benefits of implementing the blockchain and IPFS are widely assessed in the previous chapter. Nevertheless, implementation of DCDE has not been yet done in the construction sector, and this chapter aims to provide some clarification to push the utilization of the

DCDE. However, the development of distributed data storage would provide the company a potential gain concerning competitive companies. DCDE implementation could ensure future cash flows in the long term. Moreover, it would provide to the corporates an innovative and high-tech image to the firm in the sector and increase the reliability and resilience of the corporate's picture with respect to the competitors.

Regarding blockchain technology several alternatives are available depending on the strategy, budget, IT developer, size of the company and so on. Whether within the company an IT team is available and can develop their blockchain, Hyperledger Fabric protocol could be used to generate distributed ledger blockchain systems. HLF is developed to provide open-source software to the enterprise market to modify the path and how information is disseminated and the business is executed Hyperledger Foundation [2021].

Figure 3.9. Hyperledger Fabric Logo

Hyperledger Fabric is an open and neutral ecosystem for a developer to build a private blockchain network for the company. Hyperledger Fabric can "enable a decentralized, transparent network that require no central authority to validate data. In these networks, transactions are authenticated and recorded as a series of encrypted blocks, or a blockchain, creating a live, open, and immutable audit trail" Hyperledger Foundation [2021]. Moreover, the service is free since the code is open and neutral, allowing anyone to build a distributed ledger. Furthermore, one of the best benefits that differentiate HLF from other blockchains is that it is private and requires permissions. Meaning that, only those people who have authorized access called a trusted Membership Service Provider can access the network Nawari N. O. [2019].

Moreover, HLF can create channels and allow subgroups to work on a separate and "private" ledger of transactions, ensuring participants belonging to the same design team, for example, to have their string of workflow which fits perfectly the CDE framework, in terms of WIP.

Whether the company has a reliable and capable IT team to develop their blockchain through HLF, several tutorials and examples are available on the HLF website. Technically, HLF is coded on Javascript coupled with node.js which allows downloading all the development environment. The main benefit of owning their blockchain is the possibility to customize and adapt it to the need of the companies allowing also to shape DCDE and make it more efficient and flexible.

Whether any IT team is not available, or the employees do not possess the technical and IT skills necessary to work with HLF, several alternatives are available. Many blockchain platforms are now public and already developed by providers. Resulting in no need for IT employees who manage the network since it can be managed and supported by the providers. Ready-made blockchain platforms have been developed by IBM, Microsoft, Oracle and allow the users to instantly create a distributed ledger without the need for IT knowledge, strongly simplifying the adoption of a blockchain network. Hence, blockchain platforms are available on the market with the advantages of requiring a very low IT understanding of blockchains with respect to HLF. Moreover, a user interface is available facilitating the process for all the users who are approaching the technologies. In all of them, the main benefits of blockchain platforms are provided. Thus, optimization and acceleration of the workflows across the companies and the teams based on a secured environment and trusted data. A decrease in costs and in risks, increasing the accountability of softening and minimizing the conflicts that can arise. Moreover, it can lead to new monetization opportunities widening and opening to new marketplaces. Finally, the employment of blockchain can increase the level of trust among the companies in the market IBM.

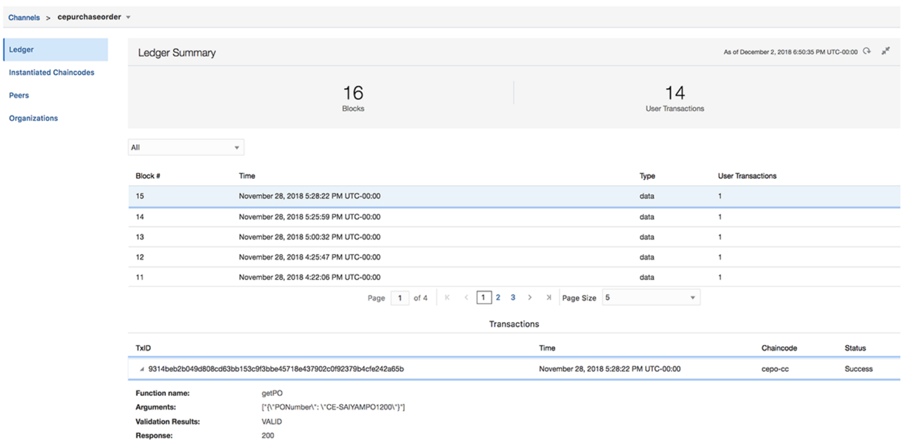

Figure 3.10. Oracle Blockchain platform User interface. Source: Oracle [2019]

Many alternatives are available for example, IBM and Oracle developed their blockchain platform, Microsoft developed Azure Blockchain and several others are possible. The price generally is around 0,30USD Price per Allocated CPU-Hour (VPC-hour). For example, the IBM Blockchain Platform is 0,29USD.

IPFS network is widely-available, free and doesn't require the installation of any software. Nevertheless, a desktop application is available to facilitate the operation. Therefore, to use the IPFS network no IT requirement or IT knowledge is needed. An improvement could be the development of an application that would facilitate access to the file also during the construction process in situ.

Chapter 4

Conclusions and Future work

In this thesis, alternative approaches to the implementation of a CDE are evaluated. Starting from the oldest approach represented from a Project Server to Cloud environments which are the most used nowadays in the industry, up to the future approaches depicted by the employment of blockchain technologies and IPFS. An analysis of the main benefits and drawbacks of the different systems and platforms. The study shows how the current platform and methodology are not adapted to the construction sector, which still maintains a rather conservative approach. Moreover, contemporaries methods and platforms do not sustain a fully collaborative environment that firmly deteriorates the level of trustness among the stakeholders, and corrupts the quality of the project output. Therefore, a new approach that sets up an immutable, reliable and secure data storage is introduced to ensure a new collaborative way of designing. Based on distributed ledger technologies like blockchain the DCDE framework is analysed, explaining how it can overcome the main issues of the centralized data repository.

Additionally, the practical implication of the introduction of DCDE is an increase in efficiency and optimization in workflows carried out by multiple parties, accelerating the performances of the process across the supply chain. A reduction of costs and minimization of disputes with a consequent gain of trustness among participants is expected. Moreover, a company that tends to employ the most recent cutting-edge technology, improves the brand's trust of investors in the market and the company's image with respect to competitors.

Nevertheless, the assessment of DCDE is limited by the lack of practical implementation which strongly restricts the evaluation and applicability in realistic study-case. And future research could focus on implementation in a real construction project in order to effectively establish the benefits deriving from a distributed storage system.

Moreover, the pandemic heavily accelerated the digital process obliging the companies to adapt rapidly to the change. It is, therefore, fundamental from the company side to define a strategic plan of digitalization in order to resist and be more resilient towards future adversity.

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