BLOCKCHAIN TECHNOLOGY - POTENTIAL APPLICATION IN THE PORTUGUESE CONSTRUCTION INDUSTRY

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Aos meus pais e família

Cristiano, gostava que tivesses visto

" A goal without a plan is just a wish."

Antoine de Saint-Exupéry

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Resumo

Com o aparecimento da Indústria 4.0 surge o conceito de Construção 4.0 e, a este associada, a a digitalização ganha um peso que impacta fortemente a construção civil. A indústria da construção apresenta uma relevância elevada nas economias dos diferentes países, pelo que o seu desenvolvimento deveria ser uma prioridade, no entanto é uma indústria por vezes classificada como ineficiente, e que inclusive não apresenta os níveis de produtividade de outros setores.

Os avanços tecnológicos que surgem com a Indústria 4.0 ainda estão numa fase inicial no que toca às possibilidades que a indústria AEC poderia atingir. Deverá, portanto, ser tido em conta que a Engenharia Civil tem um papel importante na elevação do setor, dando um impulso na melhoria de processos responsáveis por tais problemas de produtividade.

Neste contexto, a presente dissertação apresenta, e justifica, propostas de aplicação de uma tecnologia que surge no advento da Construção 4.0, a tecnologia Blockchain. Esta tecnologia apresenta diversas qualidades que devem ser tidas em conta enquanto tecnologia que poderá resolver problemas existentes na construção.

Tendo como problemática averiguar a sua potencial aplicação na indústria da construção portuguesa, a dissertação faz referência aos problemas que existem no setor, mas também uma breve explicação sobre a pertinência do aproveitamento de investimentos na digitalização, com vista à progressão na investigação da tecnologia.

Inicialmente, é feita uma introdução ao tema enquadrando-o nos problemas pelos quais atravessamos. De seguida, é apresentado um estado de arte conciso na tecnologia blockchain, especificando-se com o intuito de se compreender enquanto tecnologia isolada. Após esta explicação detalhada, são apresentadas diversas aplicações noutros setores, culminando no capítulo seguinte, onde são propostos três casos de uso de forma detalhada de onde se pode extrair informação relevante para a sua aplicação prática. Por fim, são retiradas conclusões acerca da dissertação e de que modo se poderá progredir no tema.

PALAVRAS-CHAVE: Blockchain, BIM, Construção 4.0, Payments, Smart Contracts, Supply chain

ABSTRACT

With the emergence of Industry 4.0 comes the concept of Construction 4.0 and, associated with this, digitalization gains weight that strongly impacts the construction industry. The civil construction has a high relevance in the economies of different countries, so its development should be a priority, however it is an industry that is sometimes classified as inefficient, which does not even present the productivity levels of other sectors.

The technological advances that arise with Industry 4.0 are still at an early stage in terms of the possibilities that the AEC industry could achieve. It should therefore be taken into account that Civil Engineering has an important role in the uplift of the sector, giving a boost in the improvement of processes responsible for such productivity problems.

In this context, this dissertation presents, and justifies, proposals for the application of a technology that arises in the advent of Construction 4.0, the Blockchain technology. This technology presents several qualities that should be taken into account, as a technology that can solve existing problems in construction.

Having as problematic to investigate its potential application in the Portuguese construction industry, the dissertation makes reference to the problems that exist in the sector, but also a brief explanation about why investments in digitalization should be used to progress in the investigation of the technology.

Initially, an introduction to the topic is made by framing the theme to the problems we are going through. Next, a concise state of the art in blockchain technology is presented, being specified for the purpose of understanding it as a standalone technology. After this detailed explanation, several applications in other sectors are presented, culminating in the next chapter where three detailed use cases are proposed from which relevant information for its practical application can be extracted. Finally, conclusions are drawn about the dissertation and how the topic can be progressed.

KEYWORDS: Blockchain, BIM, Construction 4.0, Payments, Smart Contracts, Supply chain

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GLOSSÁRIO E ABREVIATURAS

4IR – FOURTH INDUSTRIAL REVOLUTION

AEC - ARCHITECTURE, ENGINEERING AND CONSTRUCTION

AECO – ARCHITECTURE, ENGINEERING, CONSTRUCTION AND OPERATION

AECOPS – ASSOCIAÇÃO DE EMPRESAS DE CONSTRUÇÃO, OBRAS PÚBLICAS E SERVIÇOS

AI – ARTIFICIAL INTELLIGENCE

AICCOPN – ASSOCIAÇÃO DOS INDUSTRIAIS DA CONSTRUÇÃO CIVIL E OBRAS PÚBLICAS

AR – AUGMENTED REALITY

B2B – BUSINESS TO BUSINESS

B2C – BUSINESS TO CONSUMER

BDP – BANCO DE PORTUGAL

BIM – BUILDING INFORMATION MODELLING

CDW – CONSTRUCTION AND DEMOLITION WASTE

CPS – CYBER-PHYSICAL SYSTEMS

CSCW – COMPUTER SUPPORTED COLLABORATIVE WORK

DAPP – DECENTRALISED APPLICATION

DIPS – DECENTRALISED IDENTIFIERS

DLT – DIGITAL LEDGER TECHNOLOGIES

DPOS – DELEGATED PROOF OF STAKE

EU – EUROPEAN UNION

EVM – ETHEREUM VIRTUAL MACHINE

GPS – GLOBAL POSITIONING SYSTEM

ID – IDENTIFICATION

IOT – INTERNET OF THINGS

IP – INTERNET PROTOCOL

ISO – INTERNATIONAL ORGANISATION FOR STANDARDIZATION

IT – INFORMATION TECHNOLOGY

KPI – Key Performance Indicator

P2P – Peer to Peer

PBFT – Practical Byzantine Fault Tolerance

POA – Proof of Authority

POET – Proof of Elapsed Time

POS – Proof of Stake

POW – Proof of Work

QR – Quick Response

RFID - Radio Frequency Identification

RRP – Recovery and Resilience Plan

SCM – Supply chain management

VR – Virtual Reality

WSN – Wireless Sensor Network

1 INTRODUCTION

1.1. FRAMEWORK - IMPORTANCE OF DIGITALISATION AND AUTOMATION

Technological evolution has been strengthening across all industries and the construction sector could not be an exception. Despite its lag, in digitalisation and technological development, the construction industry is one that strongly needs boosting and, as such, investments have been increasingly aimed at that digital evolution.

Construction 4.0 comes from the fourth industrial revolution (4IR). Giving some context, the fourth industrial revolution was preceded by three industrial revolutions. The first arose with the introduction of machines into production in the late 18th century, moving away from manual production to the use of steam engines as a source of energy. The second arose at the end of the 19th century until the middle of the 20th century with the introduction of pre-existing systems in industry. Mass production began as the main means of production and the electrification of factories. The third industrial revolution is called the digital revolution with the emergence of industrial automation. Manufacturing processes evolved as well as the development of electronic technology.

Industry 4.0 has now emerged and is developing. This industry is very important for the field of civil engineering, as it is also evolving with Construction 4.0. Construction 4.0 is a term that should be seen as a leap in the built environment, with an increase in efficiency in production, business models and value chains. In fact, the focus of this revolution is the improvement of the efficiency and productivity of the processes. This focus becomes very important in the AECO sector since this problem that the revolution intends to solve is one that has been observed in the construction industry, which, in comparison with other industries, has been lagging due to the lack of incentive for transition.

The transformation or technological leap is only possible through the convergence between existing technologies and emerging technologies, which are part of the industry 4.0 paradigm. (Cornelius Baur & Dominik Wee, 2015) define industry 4.0 as a 'confluence of trends and technologies promises to reshape the things are made', which are both digital and physical. Here we integrate the concept of construction 4.0 which has the same premise that (Cornelius Baur & Dominik Wee, 2015) propose for industry 4.0, but with the purpose of reshape the way the built environment assets are designed and constructed.

Construction 4.0 combines cyber-physical systems and digital ecosystems to create a new paradigm for design and construction. To analyse Construction 4.0, we must then understand what these concepts are. Cyber-physical systems (CPS) are a fundamental driver of Industry 4.0. This concept integrates technologies that bring together the virtual world with the physical world, creating an interconnected world where intelligent objects interact with each other. The digital ecosystem concepts 'is an interdependent group of enterprises, people and/or things that share standardized digital platforms for a mutually beneficial purpose, such as commercial gain, innovation or common interest'(Rowsell-Jones et al., 2016).

In the paper 'Construction 4.0' of Anil Sawhney, Mike Riley, and Javier Irizarry (Sawhney et al., 2020b) they propose a framework for the construction 4.0 which, 'provides a mechanism via which we can:

- Digitally model the built assets that already exist in our physical world.
- Design new assets in the backdrop of what already exists or plan for the retrofit and rehabilitation of existing assets using these digital models.
- Once these assets are digitally captured and designed, use digital and physical technologies to deliver these physical assets.'

'Construction 4.0 is a framework that is a confluence and convergence of the following broad themes:

- Industrial production: prefabrication, 3D printing, and assembly, offsite manufacture.
- Cyber-physical systems: robots and cobots for repetitive and dangerous processes, and drones for surveying and lifting, moving and positioning, and actuators.
- Digital technologies: BIM, video and laser scanning, IoT, sensors, AI and cloud computing, big data and data analytics, reality capture, Blockchain, simulation, augmented reality, data standards and interoperability, and vertical and horizontal integration.'

With the use of BIM, lean principles, digital technologies, and offsite construction the construction industry is on the verge of a true transformation. The two concepts that construction 4.0 requires are in constant evolution and it is necessary to increase more and more the innovation of its processes and tools, to achieve an AECO sector as productive as possible.

1.1.1.Emerging Technologies

The Fourth Industrial Revolution (4IR) has, indeed, had an impact on the construction industry namely in emerging technologies such as:

- Building Information Modelling (BIM);
- Augmented Reality (AR);
- Virtual Reality (VR);
- Internet of Things (IOT);
- Blockchain Technology;
- Among others;

The emerging technologies provide a transformation that can be seen by tackling to the challenges of the construction sector that are listed in Figure 1:

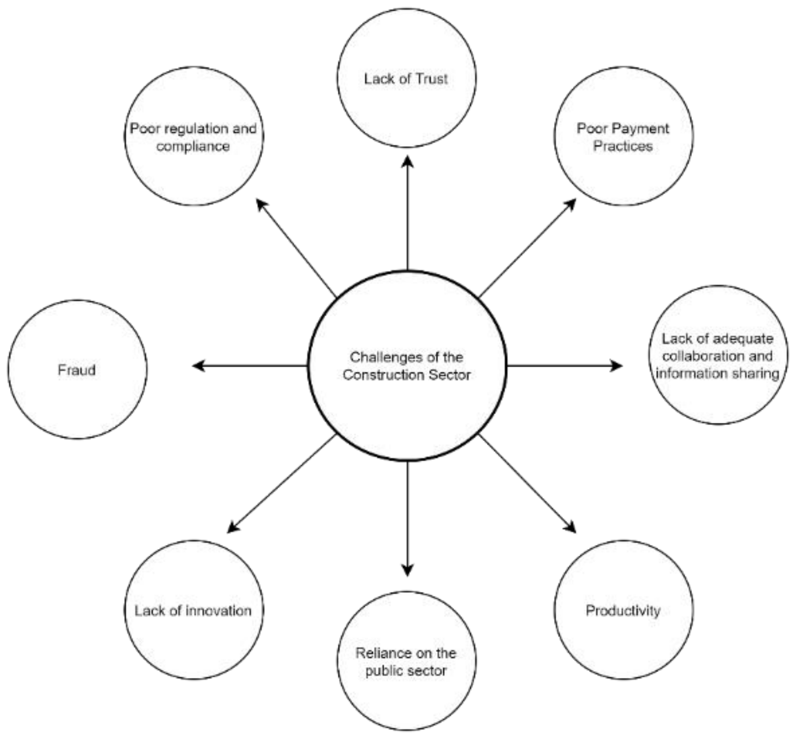

Figure 1. Challenges of the Construction Sector

As we can see from the above graph, the challenges of the construction sector must be considered when we talk about the possible impact that the technologies arising from Industry 4.0 may have on it.

1.1.2. CONSTRUCTION OUTLOOK AND INVESTMENTS IN THE FIELD

The construction industry is one of the biggest drivers of the world economy 'with about $10 trillion spent on construction-related goods and services every year' (Barbosa et al., 2017) which must bring great concerns with the low productivity when compared with other sectors. And the areas that may improve productivity are listed in Figure 2:

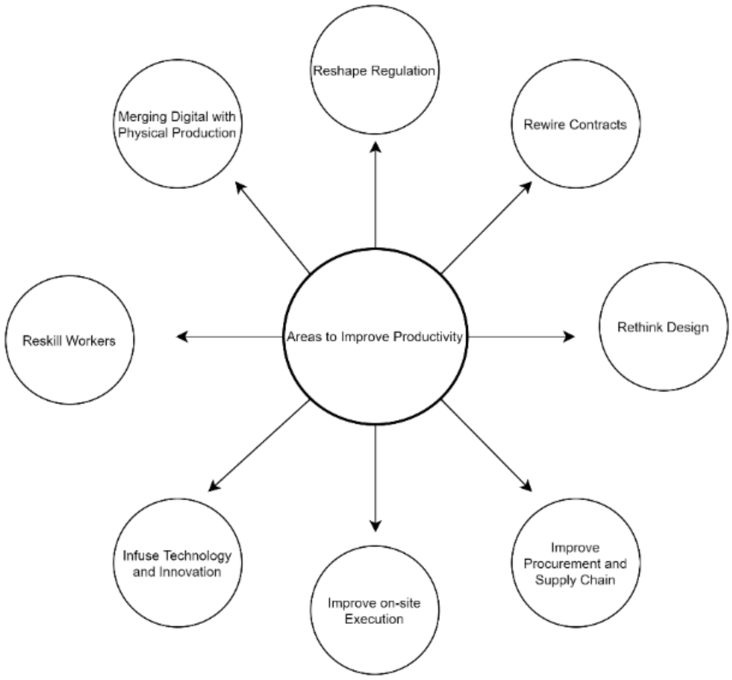

Figure 2. Areas to Improve Productivity

The global construction outlook between 2020 and 2030 expects the market to grow by EUR€4.10 trillion, to reach EUR€13.84 trillion with EUR€8.10 trillion in emerging markets. The construction worldwide is predicted to grow 3.7% in this year, according to the Construction Intelligence Center, while the average growth across the EU is projected at 2.7% in 2022.

In Portugal, according to the construction sector associations, *Associação dos Industriais da Construção Civil e Obras Públicas* (AICCOPN) and *Associação de Empresas de Construção, Obras Públicas e Serviços* (AECOPS) the *Banco de Portugal* (BdP) forecasts indicate, for the construction sector, estimated production growth of 4.3% in 2021 and an acceleration of activity in 2022, anticipating a real increase in the sector's Gross Value of Production of between 4 % and 7%, a range corresponding to an average point of 5.5%. In absolute terms, the associations indicate, based on BdP forecasts, total production in the sector should be between EUR€15.5 and EUR€16 billion. Adding the investments foreseen in the Recovery and Resilience Plan to Portugal 2020 puts the sector in spotlight, due to planned construction investments in areas such as housing, energy efficiency of buildings and infrastructure construction.

This growth in the area has highlighted several problems that previously existed but now need to be eradicated, namely problems related to low productivity and efficiency.

As stated above, the investments envisioned in the RRP are seen as an opportunity in general for all sectors. The Recovery and Resilience Plan to Portugal divides its national implementation programme into three dimensions, Resilience (RE), Climate Transition (TC) and Digital Transition (TD). Regarding the construction sector, one of the points that should be considered more is the dimension concerning the Digital Transition. This dimension has a total allocation of about 2.460 M€ with five focus areas, amongst them item C16 - Companies 4.0. This topic is dedicated to the investment made to reinforce the digitalisation of companies and to catch up with the digital transition process, in a total of 650 M€, where the aim is to encourage companies to follow this path and even to provide an improvement in the digital skills of workers that may come to be needed for the sector where they are inserted. (Governo de Portugal, n.d.)

Within the investments to be made in the light of the digital transition, Digital Ledger Technologies (DLT) are a key point to achieve the goal of increasing productivity and making good use of RRP. DLTs help to tackle the sector's challenges, notably Blockchain, which is increasingly being researched for the potential to enable solutions for the construction industry. PWC made a study where they 'analysed more than 250 emerging technologies to pinpoint those that would have the greatest business impact across industries. We called those with the most potential the Essential Eight. They include artificial intelligence (AI), augmented reality (AR), blockchain, drones, Internet of Things (IoT), robotics, 3D printing and virtual reality (VR).' (Likens, n.d.)

1.2. Objectives and Scope

The following presentation aims to present a scientific basis for the subject addressed. As a scientific basis, it is intended to provide the reader with theoretical knowledge and to make known possible ideas for innovation in a subject that is not being explored, at the date of completion of this thesis, in Portugal.

The fact that blockchain technology is a relatively recent idea in the world, makes it even more recent when it comes to its connection to civil engineering. What makes this dissertation even more outstanding is the fact that it has the intention of not only addressing the technology but also discussing possible uses in the industry.

Its use is already known in other industries, not on a large scale, but known, nonetheless. In our industry the subject is close to null, namely in the Portuguese case. The goal is to be a first approach on this matter in civil engineering, in order to encourage its potential research.

1.3. Motivation

This research thesis represents the completion of the Master's degree in Civil Engineering, in the academic year 2021/22, to obtain the degree of Master on behalf of the signatory.

This study deals with the blockchain technology and its applicability in the construction industry, with some attention to the Portuguese construction industry. This thesis presents an innovate character in its approach by the lack of knowledge around the theme and lack of practical study in the area. The problems that were presented throughout its realization were becoming increasingly difficult to circumvent, leading this thesis to have a more theoretical content presenting various approaches to this new technology in our industry.

It proved to be, therefore, a challenge that the author decided to face as an opportunity to explore new technologies that can elevate the construction sector since it is a sector in relative delay compared to other sectors.

This dissertation was carried out in a business environment, due to the author's desire to be inserted in the world of civil engineering work, but also due to the interest of the company BUILTCoLAB to address this issue.

1.4. Research Methodology

Given that this is not a report, but rather a document dealing with knowledge, it should be highlighted that this dissertation used information previously published and works that are already held as scientific truth. That is, scientific information that is uncontested in the present era. As a result, all the information utilized was obtained from trustworthy scientific sources, verifying the documents legitimacy.

The gathering of information was based on scientific articles related to the subject. The knowledge in the area is still very vague, so the research is more focused on information searches and then on practical applications that can be applied to the construction industry.

This dissertation has a theoretical content and therefore its information is based on several articles and studies. It was performed a synthesis of knowledge of the technology as an individual element and then the issue under discussion which is its applicability. At the end, after a detailed and selective analysis was made a global assessment of its advantages and disadvantages as well as difficulties of its application in the Portuguese industry.

1.5. ORGANISATION OF THE DISSERTATION

This dissertation is organized with the aim of allowing the most theoretical aspects to be presented in a summarised form at an initial stage and then evolving into more practical applications. Thus, the dissertation is divided into 5 chapters.

Chapter 1 - this chapter, in which we are, is an introductory chapter which presents the framework and contextualisation, a summary of the problem, personal motivation, the methodology adopted in the research, and the structure of this dissertation.

Chapter 2 - a state-of-art of blockchain technology is presented. That is, a synthesis of knowledge around the technology and its most theoretical concepts.

Chapter 3 - this chapter introduces the practical applications of this technology, starting by highlighting the applications in industries other than construction, to find out how they are used to consider its use in construction. Next, some case studies and articles are presented that allowed the realization of this thesis as a scientific basis of the same, where case studies are presented that relate the blockchain technology with the construction industry. It is also presented a systematic review that serves as a foundation for chapter 4.

Chapter 4 - three distinct approaches to the relationship between blockchain and construction are presented, with the aim of evaluating its possible use and how it can be applied in different construction activities.

Chapter 5 - in this chapter, conclusions are drawn from the development of the work done in previous chapters and proposals for future developments are exposed.

2 OVERVIEW ON BLOCKCHAIN TECHNOLOGIES

This chapter aims to synthesise and systemise the state of knowledge, provide a framework to the reader and to present all the necessary and relevant information for the best understanding of this dissertation.

2.1. HISTORY OF BLOCKCHAIN

The concept of blockchain emerges as a study in the early 1990s with the first blockchain network being first defined in the original bitcoin source code. The original definition came in 2008 with a publication by Satoshi Nakamoto called “Bitcoin: A Peer-to-Peer Electronic Cash system” and in 2009 the code was released as open source.

The history of Blockchain can be divided into four generations, currently entering in its fourth, Blockchain 1.0, 2.0, 3.0 and 4.0.

The first generation ran in the time between 2009 and 2013 and is characterised by being an open blockchain that was used as a simple payment method.

The blockchain 2.0 ran in the period from 2013 to 2016 and it was the time where the usage of the technology expanded. This usage focused on the economic, market, and financial applications (Zhong et al., 2020). The private platform had emerged to allow the formation of closed bookings around specific participants and its applications include smart contracts and automated stock transactions (Kim et al., 2020). Here began the adoption of smart contracts which is defined as a computerized transaction protocol that executes the terms of a contract, which can enable more complex transactions and strengthen mutual trust between users (Chambers of Digital Commerce, n.d.).

The third generation blockchain expanded the application of blockchain to other industries, which aims to provide a new paradigm for organizing social activities with less friction and more efficiency (WANG et al., 2017). Not only blockchain is used in the previous transactions but it is also used in diversified types of transactions such as Supply-Chain management (SCM) and energy transactions (Kim et al., 2020).

Finally, the Blockchain 4.0 that began in this year, 2022, has only expectations to its name, especially providing more public-accessible services, including general administrative services in the public sector (Kim et al., 2020).

2.2. DISTRIBUTED LEDGER TECHNOLOGY (DLT)

To understand what blockchain is, understanding distributed systems is essential, because blockchain is at its core a decentralized distributed system (Bashir, 2017). A distributed ledger is essentially an asset database that can be shared across a network of multiple sites and all participants within this network can have their own identical copy of the ledger. (UK Government Chief Scientific Adviser, 2015) The distributed systems are a computing paradigm whereby the nodes work with each other in order to achieve a common outcome (Bashir, 2017). It is characterized by the decentralisation operating across a peer-to-peer network, known as nodes, immutability, once blocks are chained, reliability, once all nodes have an identical copy of the blockchain which is checked through an algorithm and highlights any anomalies, and authentication (J. Li, Greenwood, et al., 2019).

Not always choosing to use a DLT is the best choice. We should be able to understand if there are any alternatives that best serve what we intend to work on. To this end, there are several mental frameworks with schemes that aim to draw a conclusion about the need and also about which architecture would be intended. A simple framework that can be used to draw our conclusions is presented below at Figure 3.

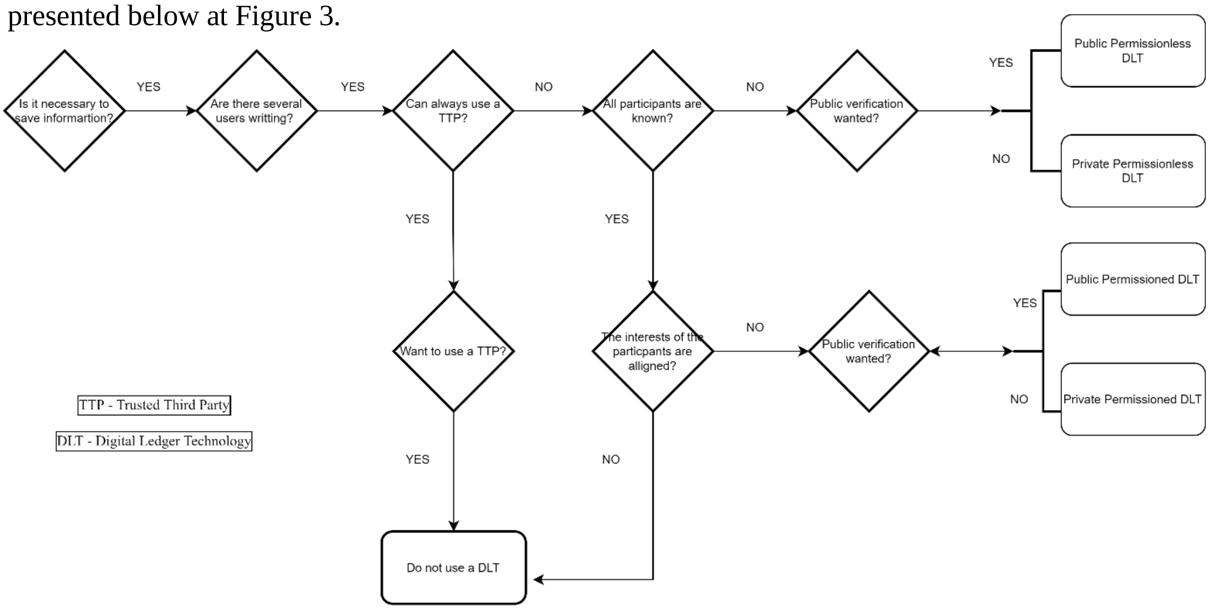

Figure 3. Framework to understand the need to use a DLT and if so what type of network

2.3. DEFINITION

Blockchain is a technology for secure decentralized data management. It is shared, immutable ledger that facilitates process of recording transactions and tracking assets in a business network. (IBM, n.d.-d) Blockchain can be considered as a distributed digital ledger that uses software algorithms to record and confirm transactions with reliability and anonymity. (Likens, n.d.)

Blockchain technology is a database that records assets and transactions over a peer-to-peer network. As a database, blockchain stores information electronically in a digital format. It allows the creation of records that cannot be tampered with. It also enables processes to be decentralized and makes the information exchanged more secure. There is a bank of records and information about a project, which is highly secured and protected through cryptography, which aims to turn any transaction into a direct process between the parties involved excluding the need for an intervening third party. There is greater security in auditing the information.

This technology is a tool that provides agility and security to the processes where it is applied. It emerges as a modern-day solution to information security. It’s a technology highly involved with the problems of trust, quality, poor regulation, and productivity of the construction industry.

Trust is key, and with this in mind Blockchain brings a solution to the lack of trust relationships between stakeholders in the AEC industry.

In the figure provided below represents a generic outline of the constitution of a block.

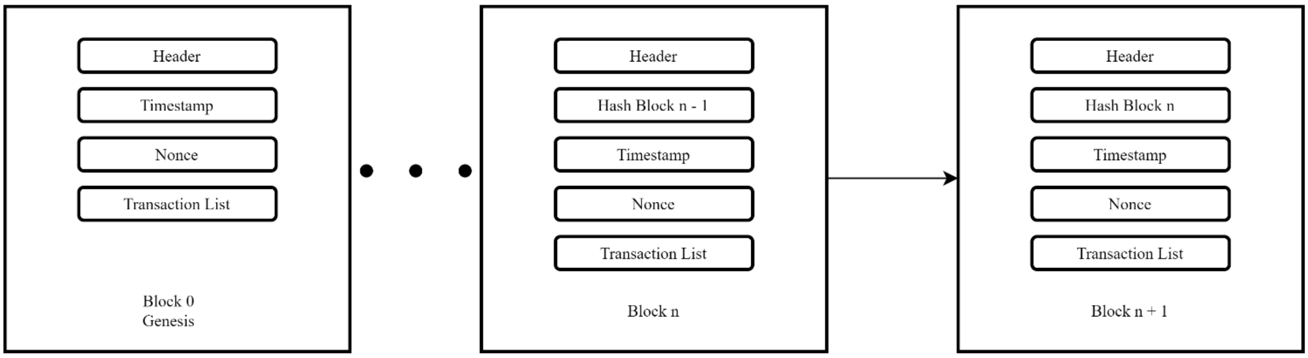

Figure 4. Generic blockchain in operation

2.4. CHARACTERISTICS

In this topic we will go through the main characteristics of blockchain technology.

2.4.1. CENTRALIZED VS DECENTRALIZED

The one characteristic that stands out right away is the fact that it is a decentralized and distributed platform.

As trust is an important factor, we will look at how blockchain decentralisation could provide an answer to the problems of lack of trust.

The simplest way to establish a trust relationship is through the reciprocal acquisition of knowledge between agents. The relationship is established directly between agents, without the intervention of third parties. We call this type of relationship a **direct trust relationship**. The next figures will demonstrate the direct trust relationships between two and three or more agents.

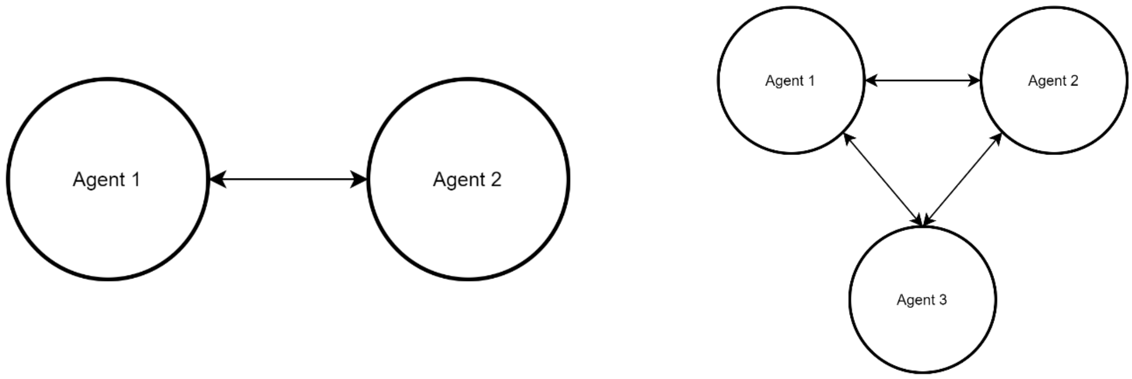

Figure 5. Direct trust Relationship and Direct trust system of relationships

Direct trust is characterized by being symmetrical, that is, it is equal in the distribution of power between agents, in the sense that all agents have the same level of autonomy and independence in the management of their trust relationships. The symmetrical condition can be exposed as in the figure below.

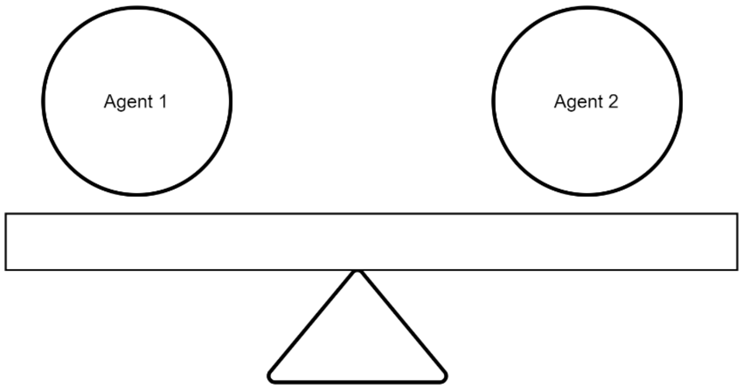

Figure 6. Symmetrical distribution of power between agents

Obviously, it is not a method applicable to all types of systems and situations. This is because as systems of relations grow, it is impossible, for reasons of cost, to establish direct relations of trust with all those present in the system. The following figure shows the level of complexity that this type of relationship can assume with only five elements.

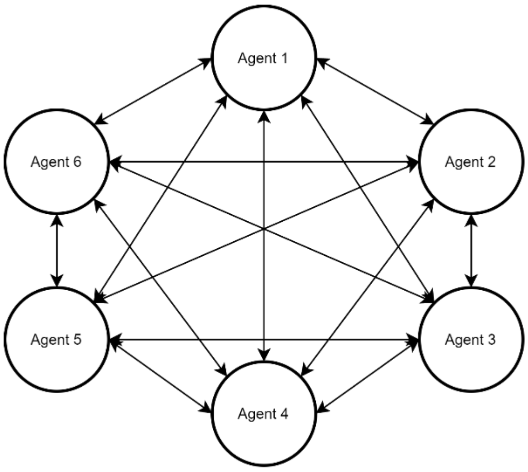

Figure 7. Complexity of direct system Relationships

To solve the scalability problem verified in the direct trust method, this new method appears. Direct and reciprocal trust relationships with each other are no longer economically feasible in systems of high size and complexity.

In this new method, named **Intermediate trust relationship method**, agents establish only a single trust relationship, with an intermediary agent, making the relationships between the other agents indirect. The agents involved, rely on the intermediary to establish and manage, with other agents, the necessary trust relationships. Thus, the agent does not have to support direct relationships between all agents of a large system. The existing relationship with an intermediary has a similar appearance to the one shown in the following figure.

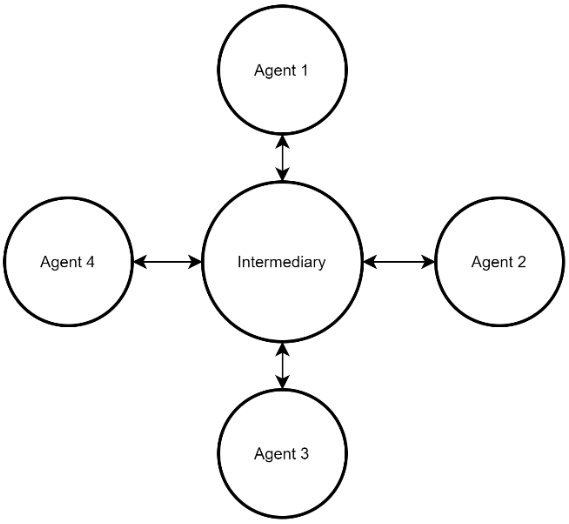

Figure 8. Intermediate trust relationship

This method is economically more efficient than the direct trust relationship method and is therefore the method used in large closed systems. It is deeply rooted in our culture and society and an example of intermediary is the bank.

This method, unlike the previous one, is asymmetrical, since by placing the responsibility for the acquisition of the knowledge necessary for the establishment of trust relationships on the intermediary, the agents transfer power to the intermediary, centralising power and losing autonomy. The figure below shows the weight that an intermediary has in relation to the agents.

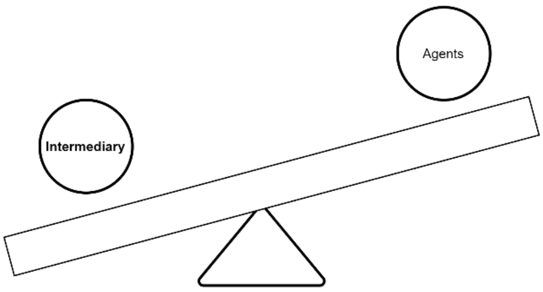

Figure 9. Weight that an intermediary has

With this method, agents no longer depend only on themselves to determine with whom, when and under what circumstances they will start a relationship of trust, and when they will end it.

Intermediation is a subject that perhaps should be discussed further since it is rooted in our societies. This debate arises with the emergence of mechanisms that combat central power, such as blockchain. Decentralisation presents the challenge of finding a mechanism for establishing trust that works efficiently and effectively in all types of systems.

Blockchain presents itself as a great solution to achieve decentralisation. It is an alternative that promises to combat the friction that can arise with intermediation. The technology contains a mechanism for establishing consensus between agents, which does not require the use of intermediaries, and which, at the same time, removes the need for agents to establish direct relationships of trust with each other. It is no longer necessary for the agents to trust each other or an intermediary agent, this trust is now placed in the consensus mechanism and in the network that supports it.

The difference between a centralized and a decentralized platform is that in the first one only one of the network participants controls and manages the integrity of the information while in the second one, all the network participants collectively store and verify the transacted information as the figure below represents.

Figure 10. Centralised vs Decentralised

2.4.2. BLOCKCHAIN VS DATABASE

The difference between an ordinary database and the blockchain is how the information is structured and stored. The blockchain collects information in groups, the blocks, which contain sets of information. Each block has a certain archival capacity, which when they become full, they close and are linked to the previously filled block, forming a chain of information known as a blockchain. This process is done cyclically with the arrival of new information that fills a block until it is full by linking to the previously mentioned chain.

While a database normally organises its information in tables, the blockchain organises its information in blocks which are linked together. This organisation creates a timeline of information when implemented in a decentralized manner. Each block receives an exact date when added to the chain.

2.4.3. ARCHITECTURE

In the interest of this dissertation, there will be presented and defined only three of the several types of blockchain that although different may share a few attributes. These three are between them the most impactful when it comes to current use of blockchain.

2.4.3.1. Public Blockchain

Public blockchain is a non-licensed blockchain that allows anyone to participate in a blockchain platform without permission. (Kim et al., 2020) In a generic way it can be looked as a blockchain opened to the public where anyone can participate as a node in the decision-making process and users, due to their participation, may be rewarded. These ledgers are not owned by anyone and are publicly open for anyone to participate in. All users of the permission-less ledger maintain a copy of the ledger on their local nodes and use a distributed consensus mechanism to reach a decision about the eventual state of the ledger. (Bashir, 2017) Consensus mechanisms are used to help the accuracy of the ledger and make sure the safety of the dispensed ledger. In this kind of blockchain, the block validators, additionally called miners, use a variety of algorithms to validate the transactions and eventually submit the showed transactions to different nodes. Only whilst maximum of the nodes affirm through accomplishing a consensus, the public ledger. Most of the public blockchains have overall performance and scalability issues in comparison to personal blockchains. Famous permissionless blockchains which includes Bitcoin and Ethereum use Proof of Work consensus algorithms, even though Ethereum is making plans to transport to a Proof of Stake consensus algorithm. One of the high-quality public blockchain packages withinside the creation enterprise may be authorities' procurement systems. They must preserve excellent governance standards which includes transparency, schedule, and accountability, for which public blockchain is one of the high-quality solutions. (Perera et al., 2020)

2.4.3.2. Private Blockchain

Private blockchain is a licensed blockchain where only authorized participants will be able to participate in the blockchain network. (Kim et al., 2020) As the name suggests, these blockchains are private and are only open to a group of people or organizations that has decided to share the ledger among themselves. (Bashir, 2017)A private blockchain is a permissioned blockchain where participants can be limited to those who are pre-approved and further it is possible to limit the participants regarding the different access levels to the information in the ledger. (Perera et al., 2020)This last point is, indeed, a very important aspect of in what way we can use Blockchain in the AEC industry, once we have a hierarchy and with the use of blockchain we can determinate what each individual of the hierarchy can access. This access and different roles are determined previously in the initiation participation phase. 'Once the transaction is submitted by the two parties involved, it would be validated by a permissioned member of the blockchain.'

We have different platforms where we can use blockchain but the one that will be more detailed in this dissertation is Hyperledger Fabric. This kind of blockchain platforms provide high privacy and security which is very essential in the construction industry, due to the fact that there is a great amount of sensitive data and information, like legal agreements and financial data, which is essential to keep private once there are some aspects that must be assured such as confidentiality and integrity. (Perera et al., 2020)

2.4.3.3. Consortium Blockchain

Consortium Blockchain has many similar qualities to a private blockchain since it is considered a partly private blockchain solution without a single owner organisation. (Perera et al., 2020) Although consortium blockchain has some of the advantages of the private blockchain, it operates under the governance of a group. Such as the private blockchain, consortium blockchain has the ability to limit the participants to different access levels. In this type of blockchain we use the Proof of Authority (PoA) as the consensus algorithm.

Consortium blockchains, can benefit the construction industry, because there are many consortia and partnering arrangements. (Perera et al., 2020) say ‘enhancing the partnering trust and transparency with high collaboration will be offered by consortium blockchain solutions.’

2.5. TECHNOLOGIES

The information is stored in blocks, and each block is constituted by basic components which are transactions, a hash value, and a nonce value. The transactions are the information or data that the network participants want to store and manage.

2.5.1. PEER-TO-PEER NETWORK

Peer-to-Peer network means that no peer is superior to other peers. A peer is also known as node, and all peers have the shared responsibility of providing the required network services. There is no hierarchy, central authority, or main server, making the peer-to-peer network purely decentralized. As soon as a block is recorded on the ledger, the whole network will have a copy of the updated ledger. (Perera et al., 2020)

2.5.2. HASHING ALGORITHM

Hashing Algorithms are used to ensure the security of information stored in blocks by transferring the traditional information into hash values. Each block of the linked blocks has two parameters, its own hash value, and the hash value of the previous block.

The hash value is unique, and in the case of some alteration to a block in the chain, the respective hash value is changed immediately. This is quite important once it is one way of providing security to the information. If someone as a hacker tries to change one hash, then the hashes in the entire chain between the tampered block and the last one need to be changed, which is impossible in the distributed environment. (Zhong et al., 2020)

2.5.3. CONSENSUS ALGORITHM

Consensus is nothing more than a distributed computing concept, that provides a means of agreeing to a single version of truth by all peers on the blockchain network. (Bashir, 2017) this mechanism is used to make sure that the block is valid before it is recorded on the ledger. So, it is used a consensus algorithm to approve and confirm transactions through a series of procedures, such as Proof of Work (PoW), Proof of Stake (PoS), Delegated Proof of Stake (DPoS), Practical Byzantine Fault Tolerance (PBFT), and so on. (Zhong et al., 2020) Table 1 gives a description of the three most commonly used types of consensus algorithm.

Consensus Algorithm	Description	Common Architectures of use
PoW – Proof of Work	It is a process with an associated energy cost, due to the fact that nodes must use computational power in order to calculate the hash value of a block with the necessary number of zeroes due to nonce change. Once the hash is discovered the node responsible gets permission to extend the blockchain with that new block, warning the other nodes and transmitting the new chain so they won't work on an already solved block. The node that succeeded gets a reward.	Public Blockchain
PoS – Proof of Stake	The idea is that nodes have a stake in the system, i.e., there is a bet of cryptocurrency tokens in the block they want to include in the blockchain. By making this bet, they are able to mine the respective block. The higher the stake, the greater the probability that the user will mine the block.	Public Blockchain
PoET – Proof of Elapsed Time	Guarantees a randomness and security through time, where a waiting time is distributed and the first user to finish the waiting time gets the next block.	Private Blockchain

Table 1. Consensus Algorithm

2.6. OPERATION OF THE TECHNOLOGY

As the name expresses blockchain is a technology that stores information in blocks that are linked with each other in chronological order. The data structure is something like what the picture below presents.

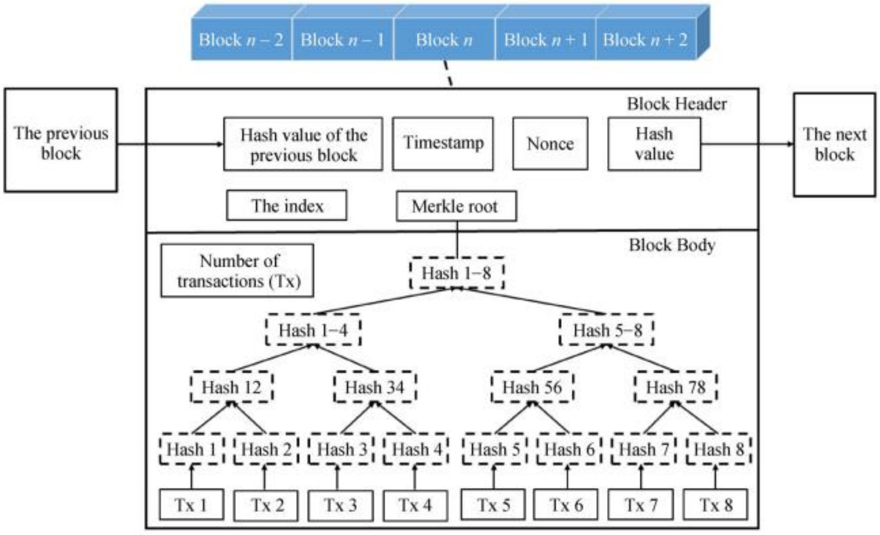

Figure 11. Data structure of a block - (Zhong et al., 2020)

2.6.1. CONTENT OF THE BLOCKS

The information is stored in blocks, and each block is constituted by components. In the picture above we have de block divided in two parts, block header and block body. The components/parameters that make up the block are the hash value of the previous block, a timestamp, the nonce value, the hash value, the index and the Merkle root. The hash value is a unique identifier of the block generated by a hash function. The nonce value corresponds to random values which make the first digits of hash values equals 'zero'. (Kim et al., 2020) The Merkle root is a final value obtained by multiple hash operations hash operations, showing the numerous transaction records of the block in the form of a binary tree, and is used to verify whether the transaction data of this block has been tampered with. (Zhong et al., 2020) The block body that is the 'root' of the Merkle root contains a set of transactions that represent the original information to be transferred into hash value based on the hashing algorithm. (Zhong et al., 2020)

2.6.2. OPERATIONAL PROCESS OF BLOCKCHAIN

A blockchain is constituted by different blocks that are built as the information and data grows. The first block designated as 'genesis block' appears by storing the default number of transaction data. As the data is registered it is encrypted with a hash value which is generated by using a nonce value. The following block, like the previous block, is generated when the default number is transaction data is stored.

Each block that appears in the chain contains its own data, its own hash and time stamp, but also has the previous block hash value. So, the chain of blocks has a chronological order that cannot be changed. A block, with exception of the 'genesis block' or Block 0, contains its nonce value which is a random value, the hash of the previous block and its own corresponding transaction hash value as the figure below demonstrates.

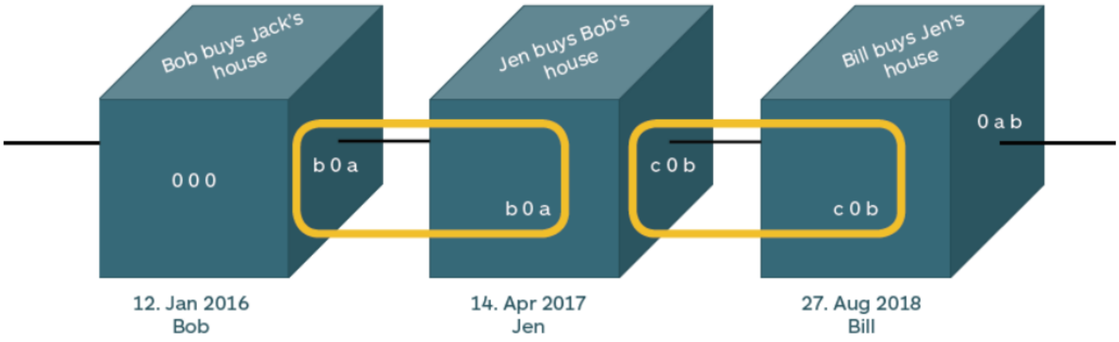

Figure 12. Basic content of a block - (BloxHub, 2019)

2.6.3. PRACTICAL PROCESS STEPS

1. Peer-to-Peer Network: someone on the P2P network requests a transaction
2. Communication: The requested transaction is shared or communicated to the P2P network, which is constituted by computers, known as nodes.
3. Validation: the node network validates the transaction and users' status using algorithms. A valid transaction may involve cryptocurrency, contracts, records, or other information.
4. Verification: Once verified, the transaction is combined with other transactions to create a new block of data for the ledger.
5. Confirmation: The new block is then added to the existing blockchain in a permanent and unaltered way.

The transaction is completed.

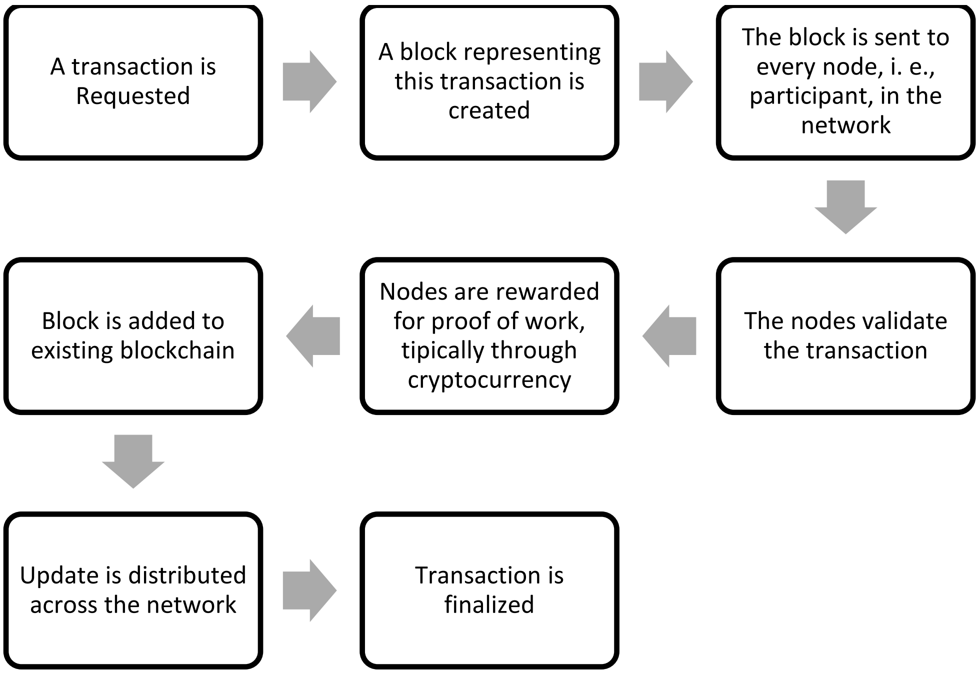

Figure 13. Process steps for a transaction

2.7. Pros and Cons

The following table presents a list of Pros and Cons of blockchain technology.

Pros	Cons
The absence of human intervention improves the accuracy in the process of verification	Substantial technological cost related to bitcoin mining
The absence of a third party in the process of verification leads to cost reductions	Reduced transactions per second
The decentralization of the decision-making core obstructs any amendments	History of use in illicit activities
Transactions become secure, private, and efficient	Regulation is unclear
Clear and reliable technology	Data storage limitation
Ensures a safe banking alternative	
Provides protection of personal information for citizens of underdeveloped countries	

Table 2. Pros and Cons of Blockchain

According to some discussions, (Amintoosi et al., n.d.) and (Tezel et al., 2020), it was possible to see that naturally there are aspects that elevate the blockchain on the AEC sector but also barriers and risks associated with it. Some that were discussed are presented below.

2.7.1. Drivers

- Increased security in data storage and retrieval
- Increased data traceability and transparency
- Fraud resistance
- Immutability and tamper-less ledger of transactions
- Streamlined procurement and payment processes
- True democratization of data and open-book procurement
- Demonstrable outcomes in other sectors, such as FinTech and LawTech

2.7.2. Barriers

- Need for high computer power
- Private blockchains are more prone to be hacked
- Scalability of blockchains
- Lack of skilled human resources
- Lack of substantial exemplary use cases
- Lack of legal foundations/regulations
- Perceived high-risks and hesitation
- Volatile Cryptocurrency values for public/semi-public blockchains

2.7.3. Opportunities

- Active software development community
- Decrease in transfer fees
- The IoT will be of the prime beneficiaries of blockchains
- Facilitate creating decentralized common data environments
- Accelerate the digitalization in the industry by overcoming concerns relating to security, ownership, and IP rights
- Facilitate various applications in commercial, supply chain, and operations management in construction
- Faster financing and allocation of payments in projects
- True sharing economy
- Direct payments to supply chain tiers by overcoming gatekeepers for interrupted value flow
- Stronger government involvement to legitimize the implementation and usefulness

2.7.4. Risks

- Identification through IP address
- Powerful organizations and governments trying to dominate and control the blockchain environment
- Limited view to the technology over cryptocurrencies
- The current “noise” and hype - a too optimistic picture of the technology
- Not knowing when to use the technology for what purpose
- Legal, operational, and contractual fragmentation in the industry

- Readiness of supply chains for true information transparency and streamlined/automated value transactions
- Lack of involvement from professional institutions in policymaking
- The existing digital difference between large organizations and SMEs may worsen

2.8. BLOCKCHAIN PLATFORMS

There are four types of blockchain networks: public, private, consortium and one that isn't quite ready to be used, which is the hybrid.

The two most popular open source blockchain platforms are Hyperledger Fabric and Ethereum. With the growth that blockchain technologies are having the question of which platform is the best so we need to explore both these platforms for us to see which one is more efficient when applied to the AEC industry.

First off, lets define what Ethereum and what Hyperledger are.

Ethereum is a decentralized platform that runs smart contracts. It's designed to carry out this while being public, distributed and a community-built technology. It's an application that is executed in a peer-to-peer network. The system isn't executed in one single computer, but rather a unique set of applications designed to exist on the internet and not to be controlled by a single entity. It works under the premise of never having interruptions, censorship, or interference from third parties. (Helfenstens Penques da Silva & Marafiga Pedroso, 2019) We use the Ethereum Virtual Machine – EVM, that writes the codes in Solidity programming language, to develop applications.

Hyperledger Fabric is a distributed ledger software developed by the Linux Foundation as a Hyperledger project. Hyperledger Fabric is an open-source platform with modular consensus protocols, which allows the system to be tailored to particular use cases and trust modes. It is a platform that offers modularity and versatility for a broad set of industry use cases. It is especially interesting when it comes to relationships within a network where there is some information that need to remain private.

So, it can be stated that the Hyperledger Fabric is a private and confidential blockchain framework that enables solutions that delivers high degrees of confidentiality, flexibility, scalability, and resiliency.

Table 3. presents a comparison between the two platforms.

2.8.1. COMPARISON

Feature	Hyperledger Fabric	Ethereum
Governance	Linux Foundation	Ethereum Developers
Description of Platform	Modular Blockchain Platform	Generic Blockchain Platform
Confidentiality	Private Blockchain	Public Blockchain
Currency	None – Currency tokens via chain code	Ether – tokens via smart contracts
Consensus	Broad Understanding of consensus that allows multiple approaches	PoW – Proof of Work Mechanism
Smart Contracts	Smart Contract code – JAVA	Smart Contract code - SOLIDITY
Speed of Transactions	Less	More

Table 3. Comparison between Hyperledger Fabric and Ethereum

2.8.2. USE CASES OF THE PLATFORMS

The two platforms should be analysed from one perspective in order to understand what form and what use we intend the blockchain to take.

The first big difference between the two platforms is the fact that one is public, and the other is private. Here we encounter a point where it is possible to understand what kind of platform we want, one like Ethereum which is public and with B2C applications or one like Hyperledger which is private and with B2B applications.

A public network appears when the developer wants to create decentralized applications for the customer to use through, for example, Ethereum Smart contracts. Anyone can join the network, and everyone has a copy of the blockchain. It is also a community-led open-source application which means that these applications don't need any confidentiality, because they are developed and hosted by blockchain developer communities around the world.

Hyperledger, on the other hand, is a permissioned blockchain network, where it is solved the confidentiality problem. Hyperledger is an application that allows you to easily create a blockchain with attention to the privacy of the organization's information. The customized blockchain algorithms enables a company to define its own and unique blockchain algorithms. Hyperledger features a great tool regarding flexibility in modifying the entire underlying blockchain infrastructure, making custom blockchains applications easier for business purposes.

2.9. SMART CONTRACTS

Making a leap to the generation that begins to have more relevance to the subject in question, blockchain 2.0 emerges with the introduction of smart contracts. Smart contracts are one of the most hotly debated topics in the use of blockchain, and it may cover the various industries despite having been initially directed to the financial markets. The use of smart contracts implemented on the blockchain in the construction industry is a subject that should be analysed in more detail and, as such, we will explore it further.

Smart contracts are self-executing code on the blockchain framework that allow for straight-through processing, which translates into the no need of manual intervention to execute transactions. (Deloitte, 2017a) A smart contract can be defined as a computerized transaction protocol that executes the terms of a contract. Smart contracts intend to satisfy common contractual conditions, including payment terms, confidentiality, liens, and enforcement. It also pretends to minimize the need of trusted intermediaries and minimize the malicious and accidental exceptions. Apart from the social aspect of the smart contracts, it pretends, on an economic point of view, reduce fraud, arbitration, and enforcement costs, and other transaction costs. (Nick Szabo, 1994)

In fact, the concept of smart contract has the aim of strengthening the mutual trust among users, once that it only runs when predetermined conditions are met. IBM define its use to automate the execution of an agreement so that all participants can be immediately certain of the outcome, without any intermediary's involvement or time loss. They can also automate a workflow, triggering the next action when conditions are met. (IBM, n.d.-b)

2.9.1. BENEFITS AND CHALLENGES

Benefits of using Smart Contracts in the construction industry:

- Accuracy - if contractual terms and conditions are recorded in a smart contract, the execution and control of these conditions is highly accurate.
- Compliance - contractual regulations requiring compliance can be implemented as part of a smart contract. in conjunction with the project information entered into the blockchain, demonstrating regulatory compliance becomes easier.
- Transparency - every payment, transaction, interaction and execution is recorded on the blockchain, making the whole process transparent and with registration.
- Cost Reduction - the information from the procurement phase is recorded in a way that is traceable, giving the possibility to evaluate the project over time and to have an insight and perception of cost optimisation. This means significant savings in general costs and in administration and control costs.
- Trust Payments and Risk Management - The smart contract network ensures this transparency and reduces a certain level of complexity in trusting that someone will change something for their own benefit. The risk of late payment and the number of disputes can be reduced.

Challenges to the adoption of Smart Contracts in the AEC industry:

- Cost of Implementation - The expense of deploying Blockchain Technology in particular when it comes to the connection with IoT, as each system or component of the construction needs to be enabled for this purpose.
- Developers Shortage - The lack of developers of the technology who have the construction sector in their sights, leading to a void when it comes to customised products and services for this sector.
- Slow adoption of new technologies by the industry - lag in industry adoption of new technologies creates low demand and therefore also low supply.
- Low awareness of the benefits - The scarce knowledge and understanding of the benefits of this technology for the AEC sector, leading to a lack of investments in research on new technologies such as this.

2.9.2. How Smart Contracts Proceed

Smart contracts follow statements written into the code on a blockchain. These statements are of the type if, when, etc. Once the predetermined conditions have been met and verified, a network of computers execute the actions of releasing funds to the appropriate parties, sending notifications or issuing a ticket, for example. Then the blockchain is updated as soon as the transaction is completed. Because it works on the base of a blockchain, the transaction cannot be changed, and only parties who have been granted permission can see the results.

In the context of a smart contract, there can be as many terms as necessary to satisfy the participants that the task is completed successfully. To define the terms, the participants must establish how transactions and their information are represented on the blockchain, agree on the if, when kind of statements that rule those transactions, scrutinise all possible exceptions, and define a framework for dispute resolution.

Thus, the smart contract can be programmed as pleased by a programmer, even though enterprises using blockchain for business provide templates and other instruments to simplify the structuring of smart contracts. An example of this are DApps, Decentralised applications.

2.9.3. DApp

A Decentralised Application is, according to (Perera et al., 2020), after a study on the paper of (X. Li et al., 2020), a definition of a smart contract that runs autonomously without the assistance of a third party. It is stable, traceable since it the data is stored in the blockchain, and secure also because it runs in the blockchain, which gives a great level of transparency.

2.9.3.1.How to create a Smart Contract with an online platform

The Figure 14. pretends to be a simple guide of how we can create a smart contract using a DApp:

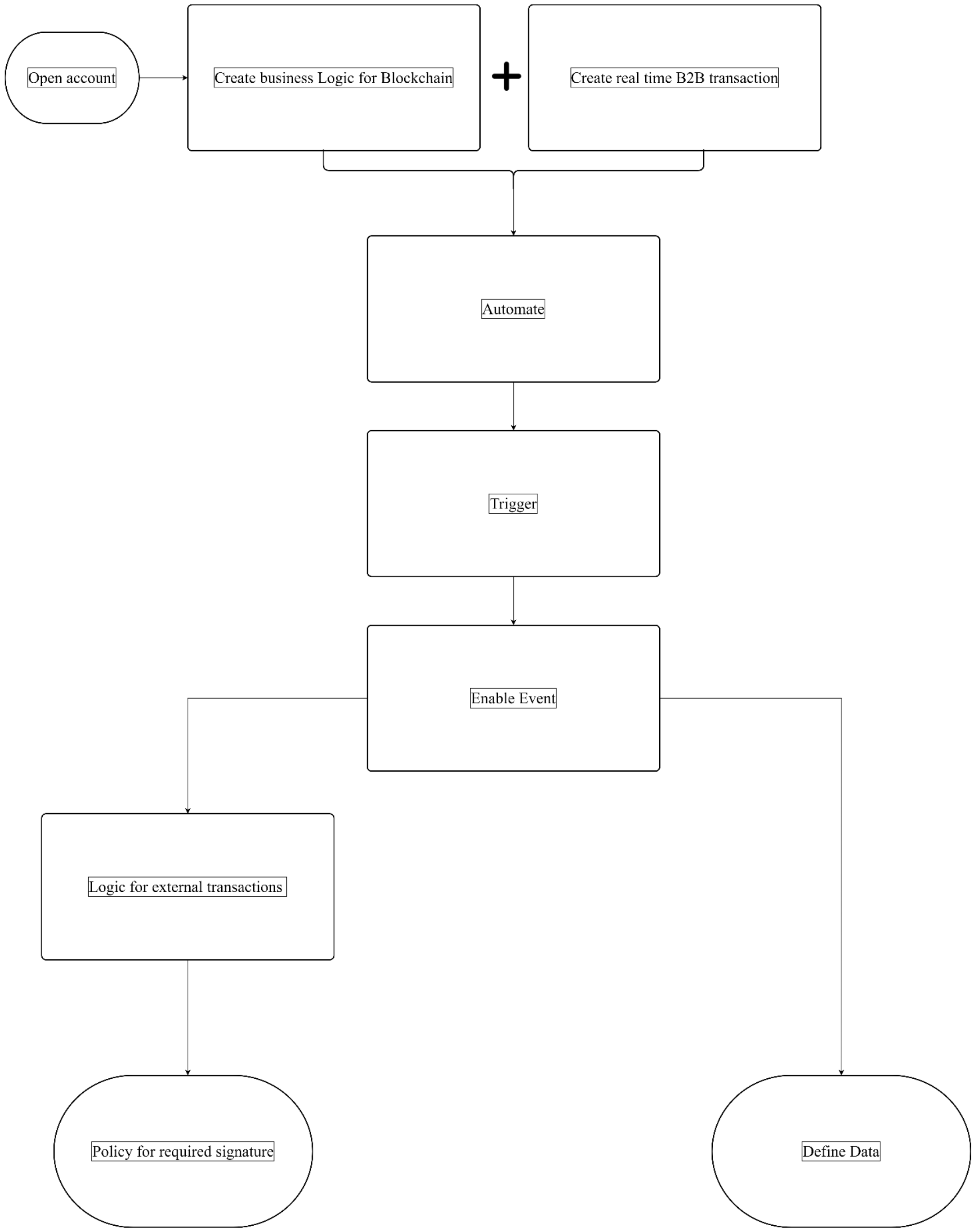

Figure 14. Smart Contract creation

3 BLOCKCHAIN APPLICATIONS

In this chapter, the different approaches of blockchain will be analysed, including the different industries, the potential in the construction industry and the different specifications and possible future case studies.

3.1. AREAS OF APPLICATION ACROSS DIFFERENT INDUSTRIES

Based on the research done, one aspect that was mentioned several times was the use of blockchain in several industries. Its usefulness goes much further than what is being studied today.

As previously mentioned, blockchain evolved in different generations, and throughout its evolution its use was spread across these different generations. Those considered most relevant from the perspective of being able to be replicated in the AEC will be presented below, although its development has been happening in other industries.

The areas to be explored are:

1. Finance Sector
2. Agriculture Sector
3. Humanitarian Causes
4. Health Sector
5. Logistics Management
6. Public Administration
7. Energy Management
8. Content Monetization
9. Property Management
10. Identity Protection

3.1.1. FINANCE SECTOR

Blockchain technology has an impact on the transformation of the financial sector, which is why, according to MingXiao et al., the world's largest banks have started to explore the application of the technology in the banking sector in order to be aligned with the developments of the technology. (Perera et al., 2020)

According to IBM 91% of banks had invested in blockchain solutions by 2018, 66% of institutions expect to be in production and running at scale with blockchain and 73% of central bank survey respondents would require retail Central Bank Digital Currency to be available under all circumstances and for all types of payments. (IBM, n.d.-a)

What it brings to the financial sector:

Fraud Prevention – As information on a blockchain cannot be tampered with, it is impossible to manipulate contracts, records of previous blocks of data and payments.

Faster Settlement - Due to the P2P transfers of funds between financial institutions we remove friction and accelerate settlements.

Smart Contracts - As an automated tool, with its easy verification and advanced execution, its use allows to reduce legal formalities and carry out high value transactions in a more simplified manner.

A problem that the sector presents is the cost of worldwide remittance transactions, and according to the world bank is estimated to cost an average of 7.3%. There are companies that intend to find alternative payment solutions to the current payment networks. One example of these companies is an American fintech called ABRA – A Better Remittance App. The fintech is based on bitcoin's global decentralized payment infrastructure, aiming for an open global financial system that is easily accessible to everyone. (ABRA, n.d.)

3.1.2. Agriculture Sector

A problem that this sector presents is related to traceability, where the final consumer has no way of verifying the origin of the products. The traceability coming from a blockchain improves the transparency and efficiency of the agents involved in the supply chain, from the farmers to the final consumer. Nowadays most of the agricultural companies use databases to store and manage data, while in a blockchain the information is stored in a decentralized way where each stakeholder can see and follow the information from the origin to the final consumer.

In terms of case studies where we are starting to think about the subject and how to improve, we have the example of Walmart's retail corporation that together with IBM started the development of a blockchain in order to track food and the example of Grass Roots also with the main aim in traceability.

3.1.2.1. Walmart case study

The partnership between Walmart and IBM was intended to create a food traceability system based on Hyperledger Fabric aiming to trace mangoes stored in its US stores within 2.2 seconds. They, then, made several more experiences culminating in proof that the concept is valid becoming in a pioneer in food traceability. (IBM, 2018)

3.1.2.2. Grass Root Farmers' Cooperative

Assumes that the future is here. This company places information on its products that gives access to its supply chain giving a certainty to the consumer that the product would not be falsified or adulterated. (Grass roots, n.d.)

3.1.3. Humanitarian Causes

Humanitarian organizations are turning to blockchain technology to transform the way they deliver aid. The integration of this technology allows aid to reach those who need it most directly, quickly, more secure, in a transparent way and without intermediaries, reducing the risks of these operations.

An example of this application was made in 2017 by the United Nations world food programme in the province of Sindh, Pakistan, where they used an alteration to the blockchain of the Ethereum blockchain turning it into a private Ethereum network to execute the first phase of the Building Blocks project. This project uses blockchain technology to increase the efficiency and effectiveness of the humanitarian aid provided by the United Nations. Its first use was aimed at authenticating and recording payments with purchases made by aid recipients from sellers participating in the project. The use demonstrated the technology's potential to reduce the costs that the United Nations and donors incur with more traditional forms of humanitarian aid. The risk of fraud was also mitigated, namely associated with identity theft or falsification, which is essential to get the aid to those who really need it. the building blocks programme helped the world food programme distribute aid, on the "money-for-food" genre, to more than 10.000. Syrian refugees in Jordan. (Tissa Riani, n.d.)

The United Nations and the world food programme are working to develop humanitarian aid, supported by blockchain technology, to serve their future food assistance operations. Thus, the experiments carried out have demonstrated how technology can be a lever for humanitarian aid organisations.

3.1.4.Health Sector

Data recording and medical confidentiality are at risk from the storage method used, as patients' medical data are often distributed over several organisations. The implementation of IT systems is crucial to improve the sector in the way information is stored, processed, and exchanged between patients, doctors, and organisations. The processes of storing information have some problems associated, whether it is loss of data, such as unnecessary repeated examinations due to the loss of a medical record. Another issue may be related to the leakage of personal information, such as telephone number, address, email address and perhaps medical diagnoses.

A challenge is to have a central database where information can be accessed and transferred on demand to wherever you want. Blockchain introduces data protection with great care, prevents leaks and reduces the distance between agents. This technology brings answers that affect the current system, such as the difficulty of access to certain records. A network that can involve different agents such as doctors, pharmacists, and patients allow them to consult the information at any time, since it facilitates the creation and sharing of a single database provided by different agents. Thus, with the authorisation of the patient it is possible to access with high security the data that is intended to be known when necessary. The search for data is faster and therefore becomes an advantage by reducing the search time for records. Normally a service provider does not have access to the data record in another service provider.

The ideal situation would be that the medical data of a patient generated ate different points of interaction of the patient with the health systems, should be able to be collected, integrated, and controlled by the patient who would define, at each moment, who could have access to that data.

With this in mind emerges MedRec, a company created by Massachusetts Institute of Technology (MIT) researchers that has developed a system based on the Ethereum network to do just that. Through a private blockchain network, patients can control their medical data, including clinical information and data obtained through wearables, and proceed to share that information with health providers in a secure and controlled way, because it manages who can view and edit that data.

Unlike a typical blockchain network, the consensus does not reward miners with virtual currency attribution. As MedRec does not have virtual currency, the miners are doctors who do medical research. The community of medical researchers provides the computing power to ensure the operation and security of the network and is rewarded with the permission to access aggregated and anonymous medical data that has been previously approved to be accessed by patients.

The research continues to be registered in the service providers' systems but is also simultaneously registered in the MedRec network.

3.1.5. Logistics Management

In this area, the supply chain is one of the sectors where the applications of blockchain technology have been the most experimented. A blockchain network provides a great traceability, transparency and management processes becomes easier, and so there is a great potential in supply chains in the tracking part specially. The use of blockchain in the supply chain will allow the existence of certifications and documentation, including lifecycle information of a product accessible to all agents involved, giving the certainty that the information cannot be adulterated along the supply chain.

According to a study by Deloitte, the inherent risks are associated with its increasing complexity and some risks are associated with the search for efficiency and cost reduction of operations. Deloitte in its report identifies that the guideline for an ideal supply chain is to have a visibility of all the supply chain from end-to-end, the ability to adapt quickly to problems that may arise without unnecessary costs, the trust between agents is not necessary, but the agents must only trust the system, and control parameters are of extreme importance. (Deloitte, 2017b)

Deloitte highlights the interconnection of blockchain technology with IoT identifying four challenges that these technologies together can overcome. Since blockchain is an immutable and irrevocable network, the sharing of information between the different stakeholders will be something that will ensure traceability and reduction of certain risks. The blockchain by being fast and transparent allows access to information, when necessary, at any point of the supply chain. The IoT allows a link to be made between the physical and an information network, i.e., the data will be connected to the materials and products and all their transformations will be followed throughout the supply chain. The blockchain will reduce the risks of fraud and ensure that the codes of conduct are always respected.

An existing practical example is the Everledger blockchain. This platform is built on the foundation of a private blockchain. It allows information to be accessed and shared securely and smart contracts to be enforced. Everledger has been applied, for example, to the diamond industry by the Brilliant Earth brand. It makes a point of having a register where it can securely track the origin of its diamonds, giving greater security to its customers.

3.1.6. Public Administration

Low voter turnout is an existing problem in many nations including Portugal. In order to increase this turnout, online voting could be an alternative. This alternative presents many doubts, due to fears of lack of security, fraud, and trust in such a system.

With the idea of reducing the abstention rate, a company based in Cleveland called Votem has emerged, that works on the emission and traceability of mobile and online votes emitted by displaced voters, presenting several case studies.

Their solutions include an online voting platform called Castlron Platform, which is built on a blockchain, ensuring organizations and governments an electoral management platform for secure, transparent and 100% verifiable elections.

3.1.7. Energy Management

Blockchain technology in this sector could help reduce operating costs and offer new services. A DLT could be used to exchange energy between individual producers and consumers. Renewable energy is very much in vogue and so blockchain can be used by producers and consumers to exchange this energy with transparency, traceability and other benefits.

According to Global Market insights Inc. “Blockchain technology in the energy market is predicted to rise from USD 200 million in 2018 to around $18 billion by 2025”. A few platforms have emerged with the aim of providing services on the energy market through blockchain such as Powerledger. According to their website, Powerledger sees blockchain as “something akin to barcodes in supermarkets.”, and the explanation to this comparison is actually quite logical, as the barcodes don’t define what a supermarket is but allows them to operate at high volumes and low margins.

This fast, transparent, and secure technology enables Powerledger to create and help manage projects across the globe. The company currently operates on the POA Ethereum consortium chain and is currently testing its own Solana based Powerledger Energy Chain.

3.1.8. Content Monetization

Social networks enable us to maintain active social relationships and allows us access to large amounts of information and content creation and distribution.

When we create an account on a social network, we provide our data. This data is then used, by means of algorithms present on the social networks, to identify which content will be more of interest to us. This interest that we provide in monetized by the social networks through selective advertising paid by its promoters. This monetization is only made and received by social networks, without any kind of sharing by those who are at the genesis of the creation of this value, the users.

In March 2016, in order to give more power to the user, the Steemit platform was created. This platform is supported by blockchain network called Steem and two virtual currencies, the steem and steem dollar. This network remunerates users for their interaction with the platform. The user interaction can be in creating new content, commenting on other users’ content or even upvoting. The remuneration is given in the platforms virtual currency that can then be converted into fiat currency.

3.1.9. Property Management

Property registration is something that is often unknown, with a lack of information on landowners, or former owners, certificates, and so on. Blockchain has features that allow asset tracking, ownership transfer certifications, and can also allow for greater legal security below cost, with an immutable record of property’s history. There are several countries where disputes over land are quite common, and this is due to the fact that there is a lack of registration of these lands.

ChromaWay is a blockchain technology company which is the creator of relation blockchain. It is a blockchain that combines the power and flexibility of mature relational database with the secure collaboration and disruptive potential of blockchain. They are presenting solutions in land administration, real estate, finance and tokens & E-Currency. Most interestingly, in land administration they are investigating the use of smart contracts and blockchain for the process of selling houses, and, in partnership with the Andhra Pradesh government, have built a blockchain based system for property registration, showing potential in eliminating fraud and errors and also reducing administrative hassle.

3.1.10. Identity Protection

Identity theft is a major crime happening around the world. Blockchain is identified as an ideal solution for identity theft, once it is immutable which means that it is impossible for a hacker to alter data without the permission of at least 50% of the nodes.

What is to be done is to deposit Decentralised Identifiers (DiDs) on a blockchain with personal data, from name to social security numbers, to which a person will receive a QR code that can be stored in a digital wallet. In practical use, when accessing an application, instead of putting the data in again, you just pass the QR code.

The SelfKey Foundation vision is to help develop a decentralised identity ecosystem. Its idea is to move from paper-based systems to a digital, private, secure, transparent identity with individual right.

3.2. Blockchain Integration

This chapter is intended to make a connection between the previous chapters before delving into the specific role that Blockchain can play. We will analyse how Blockchain brings answers to problems that construction presents and that can be solved.

Blockchain brings opportunities to overcome inefficiencies related to the complexity of construction, notably with regards to design, financial and legal considerations. The construction process is fragmented and coordination between the various actors is often suboptimal, resulting in loss of productivity, delayed progress, rework and, in consequence, increased fees.

Throughout the entire supply chain of a construction site, there are several players:

- Sponsors - Client, Financiers
- Project designers and design team
- Contractors
- Supply chain - Product manufacturers and suppliers
- Operation team
- Users - Residents, customers, etc.

“The fragmentation of information in construction projects are a persistent problem characterized by a disconnect between design and construction” (Bryde et al., 2013) This statement makes sense due to the lack of open and trusted distribution of coherent and cohesive information among all stakeholders. (Sawhney et al., 2020a)

Blockchain has the potential to subvert some of these effects through open and transparent transactions, particularly if coupled with BIM processes. BIM is the natural choice to accelerate digital transformation as it brings architecture, engineering, and construction professionals together in a collaborative work supported by computer becoming a Computer Supported Collaborative Work (CSCW).

Once the IoT has enough information the Blockchain should be the mechanism that dictates how the information will be distributed.

“Intelligent contracts appear as a logical extension to BIM whereby the contractual performance itself becomes automated” (Maciel, 2020) Blockchain in the procurement phase can be used to effect contracting if both parties agree to respect and produce a result more quickly. This contracting can be more easily incorporated into anticipated litigation, such as in construction contracts.

Blockchain will enable the effective and reliable tracking of materials, components, and entire products throughout the supply chain and into their reuse. However, the precise connection between physical and digital records remains problematic. If resolved there is great potential to create a perpetual cycle of use of units, elements, and products.

Blockchain can play a significant role in facilitating new business models and new transactional requirements in the construction industry. It makes it possible for BIM platforms to be operated through smart contracts, signalling the team when to initiate a particular transaction and further automating construction procurement processes from the ground up.

3.2.1. Blockchain Connection with other Technologies

Blockchain is highly connected to other emerging technologies linked to different industries. In the case of Civil Construction, blockchain is linked to technologies such as the Internet of Things, Radio Frequency ID, Building Modelling Information (BIM), Wireless Sensor Network (WSN), Smart Contracts and so on.

3.2.1.1. Internet of Things - IoT

According to the International Telecommunication Union (ITU) in 2012, "IoT is a global infrastructure for the information society enabling advanced service by interconnecting (physical and virtual) things based on, existing and evolving, interoperable information and communication technologies." And according to the International Organization for Standardization (ISO) in 2018, IoT is "an infrastructure of interconnected entities, people, systems and information resources together with services which process and react to information from the physical world and from the virtual world".

In recent years, many advanced sensor applications have been developed to give objects the ability to sense light, temperature and motion sensors and RFID. With sensors, the object acquires a sensing capability so that it can understanding its condition, or can recognise or be recognised, in the same way as human vision or hearing. Big data can be collected automatically and analysed, allowing things to exchange information with each other.

The IoT comprehends a series of technologies with the capabilities mentioned above, Radio Frequency ID (RFID) and Wireless Sensor Network (WSN) are some that stand out the most. RFID uses electromagnetic fields to automatically identify, and track tags attached to objects. WSN is a technology that comprises sensor and network technologies. it consists of functional wireless sensor devices that can intelligently collect and communicate information and even judge and act.

3.2.1.1.1 Process

The IoT has different layers that work within five steps: create, communicate, aggregate, analyse and act. So firstly, there is a sensor attached to "things" that create data and trigger the flow of information. There may be automated instructions from upstream and execute an action. Afterwards there is the use of networking equipment to communicate data from the sensors and connect it to the internet, where it is included the hardware, software, and messaging protocols. Then, it appears integration, where is aggregated the sensor data and integrates it with other external data for analysis that occurs in the augmented intelligence layer. In this step we also manage the sensor and network elements. The augmented intelligence takes raw data downstream, analyses it and derive actionable insights. We have two variants of information flow, one with data in motion, and another with data at rest. At last, there is the use of the insight derived from IoT data to automatically trigger changes in human or machine behaviour.

The Figure 16. is a representation of the connections between BIM, IoT and blockchain, demonstrating how they can cooperate.

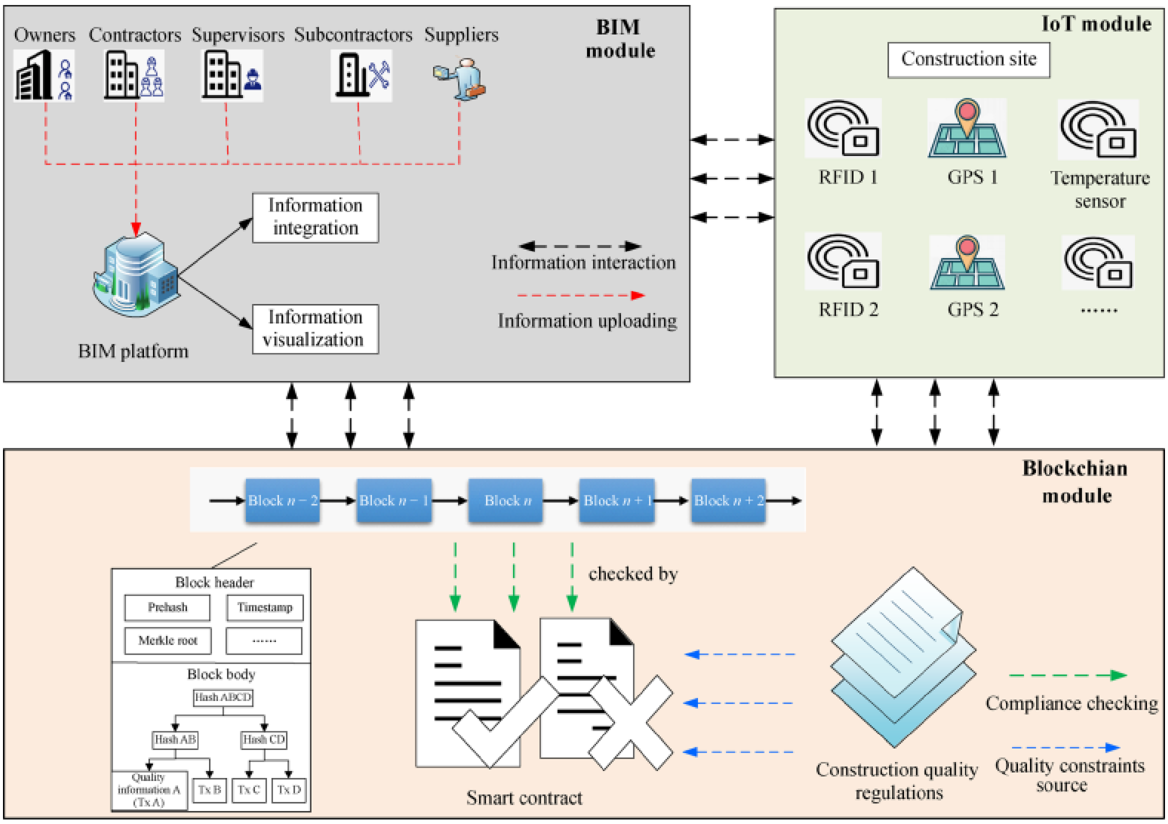

Figure 15. BIM IOT and Blockchain Integration - (Zhong et al., 2020)

3.2.1.2. Building Information Modelling - BIM

According to ISO 2016 BIM is 'a shared digital representation of the physical and functional characteristics of any built object (including buildings, bridges, roads, etc.) providing a reliable basis for decisions.'

In practice, IoT devices provide the state of things information, and their positional information can be linked to the BIM model so that spatial links and real-time states can be displayed simultaneously. BIM provides a framework for IoT data to be integrated and analysed in a way which is meaningful for building management. The integration of IoT and BIM information can facilitate Cyber Physical Systems (CPS) for building project management.

The integration of BIM and IoT establishes a virtual reproduction of building projects, where IoT provides the dynamic information of people, facilities, assets and building status, and BIM provides the framework for IoT data that can be systematically integrated and spatially demonstrated.

3.3. Case Studies and Articles

In order to deepen and validate information on the theme addressed throughout this dissertation research was conducted in scientific databases such as Google Scholar, Science Direct, ResearchGate and IEEE Access.

This research followed the entire development of this dissertation, and 22 relevant scientific articles were identified, which fit into the theme addressed. The phrases most used in the search engine of the databases were "Blockchain", "Smart Contracts", and "Blockchain in Construction".

Thesis related to this theme were also consulted and, also, consultant's report which served as support and structuring of the concepts mentioned. The table below presents a list of the 22 documents consulted and then a brief description of each of them.

(Zhong et al., 2020) presents a study where it starts identifying the lack of trust as a problem of quality management in the construction industry. This article presents a framework for the use of a blockchain network in a consortium architecture for construction quality information management. By identifying the problems in this area, it presents the merits that blockchain brings and solutions that could be supported by blockchain. The study focuses on the collaboration of BIM, IoT and blockchain technologies and explains how the transactions take place in a consortium network.

(Tezel et al., 2020) presents an article where, after research work, it investigates the potential of blockchain technology in construction and its future directions. Identifies the potential and challenges of the technology in the industry. The study aims to understand the strengths, weaknesses, opportunities, and threats of deploying blockchain technology in construction through interviews with 17 experts in the field and 10 recent, to the date, industry, and policy reports. The topic of opportunities stands out, as it is the one that presents the most results, however the most "negative" topics, weaknesses and threats, are somewhat extensive. The study revealed that the strengths that were most mentioned were in fact the advantages associated with information security, traceability and transparency, and the potential ability to create a P2P economy by eliminating the third-party intermediary.

(Christidis & Devetsikiotis, 2016) were motivated by the explosion of interest in blockchain, carrying out an examination on the interaction of this technology with IoT. After a review of the technology, also investigating the issue of smart contracts, they study the combination of blockchain with IoT. They conclude the study with the confidence that the combination of the two technologies is powerful and can bring significant transformations in various industries.

(Kim et al., 2020) article presents a study that aims to discover ways of applying blockchain technology to the construction industry. For this purpose, areas such as construction lifecycle and project management are used to develop a survey. The information was then analysed through an importance performance analysis method.

(Perera et al., 2020) presents a critical analysis of the potential application of blockchain in construction through a case study analysis. This analysis concludes that, due to the exponential uses of blockchain and investments involved, blockchain does indeed have potential in the construction industry. This paper outlines a number of applications in the industry and in various industries outside of construction, which is very pertinent to understand the various uses of the technology and how to adapt it to the AEC industry.

The (WANG et al., 2017) article is one of those that also identifies the lack of trust as a common problem in the construction industry and, as such, management suffers several challenges in sharing information and automating processes. We are presented with an investigation of the potential application of blockchain technology, namely three types of application that are proposed.

(Sawhney et al., 2020a) book was particularly useful to understand how the evolution of construction 4.0 came about and how it is happening. It is also important because it is the junction of several articles that became very valuable, namely the articles that explain construction 4.0 as the first article by (Sawhney et al., 2020b) and the 20th article by (Maciel, 2020) that explains the use of blockchain in construction 4.0.

(Yang et al., 2020) article discusses the different blockchain architectures, public and private, and the applicability of both in the construction industry with two practical cases. The architectures are based on the Hyperledger and Ethereum platforms and illustrate the process, benefits, and challenges of adopting both.

(Elghaish et al., 2022) paper proposes a financial management system based on Hyperledger fabric and chain code solutions that aims to tackle problems that may exist in the financial management processes of construction projects. The objective of this system is to introduce a decentralised financial management system to deal with financial issues throughout the various stages of construction through blockchain technology. Furthermore, the system is tested on a real case project with positive results, as they corroborate the usefulness of the technology.

(Cai et al., 2018) analyses the development of blockchain systems, with special attention to the importance of decentralised applications (DApps). They analyse the state of art of the technology and investigate future developments in the area of blockchain in order to achieve the desirable characteristics of a DApp.

(Zheng et al., 2020) article is comprehensive in understanding a smart contract, in the sense that it presents the challenges of the technology, the existing advances and also the platforms for its implementation. It is important to understand how smart contracts work, and as such, this article provides an explanation of how it works and how to deploy it.

(di Giuda et al., 2020) presents an investigation of digitalisation processes starting from Smart Contracts. It applies to the design phase developed in BIM, focusing on the advantages and limitations. This study presents an approach that can be applied in real and practical case studies.

(Khalfan et al., 2022) paper identifies possible applications of blockchain technology in project procurement and management, presenting a guideline to implement blockchain in project management to improve current practices of project and procurement management. In 38 identified problems the blockchain presented the ability to solve 25 of these problems.

(Kifokeris & Koch, 2020) in this paper the concept of a sociomaterial blockchain solution for integrated information, material, and economic flows is offered in this study as a new digital business model for independent construction logistics consultants. They provide an understanding of the economic flow, emphasize the optimization of construction logistics through flow integration, examine current approaches to understanding blockchain, use sociomateriality to envision a suitable blockchain solution, and consider how blockchain can be incorporated into the value proposition of a related digital business model.

(Liu et al., 2019) article aims to explore the potential of integrating BIM with blockchain for sustainable building design information management. The model presented refers to the interaction of

BIM with blockchain for the coordination and collaboration in the different phases of construction for sustainable building design. It presents the benefits of blockchain to overcome the challenges related to the industry when using BIM for sustainable building design. They also talk about the smart contract system to improve the process of using BIM as a user. They propose a conceptual architecture of BIM and blockchain for Sustainable Building Design Information Management Framework in building project management.

(Ni et al., 2021) article analyses the development and promotion of blockchain technology in construction projects, merging blockchain and BIM. It attempts to bring new ideas to the whole life cycle collaborative management of digital construction.

(Hunhevicz & Hall, 2020) paper intends to reduce the lack of knowledge regarding use-case ideas and the implementation of a DLT system. As the exploration of this area is very limited, this study proposes an analysis on possible DLT options, based on the desired characteristics, and analyses use case based on a new framework.

(J. Li, Greenwood, et al., 2019) The objective of this study is to analyse the state of DLT in the built environment and the construction sector, in order to support the adoption of DLTs in the construction industry. This study presents a state-of-art analysis, identifying 7 categories of use, proposes a framework for implementation through a system of 4 dimensions, social, policy, technical, and process, and also appraises three specific use cases.

(J. Li, Kassem, et al., 2019) This article is interesting because it proposes the integration of DLT, BIM, IoT and even smart contracts, with a simulation demonstration. The article analyses the interaction between the different technologies and the complementarity that they can present to each other. The simulation that they do reveals how a mini smart contract, for a limited scope such as an installation activity work, can be executed within the proposed approach and how payments can be automated when project delivery is coupled with machine-readable BIM requirements and contract clauses. They also refer the limitations and challenges to its adoption.

(Hamledari, 2021) This dissertation is presented as a submission for a PhD requirement. This dissertation presents a study of the impact of blockchain-enabled smart contracts on the visibility of construction progress payments. The research objectives were divided into two. one for assessing the information visibility in today's digital payment solutions and those relying on blockchain-enabled smart contracts and another for assessing the resilience of conventional and smart contract-enabled payment solutions in the face of increased granularity. A Charrette Test Method was applied in order to compare the visibility in two payment methods, one based on leading commercial software and the other based on smart contracts. The results were promising for the application of smart contracts. However, a correct adoption will still take time.

(Hunhevicz et al., 2022) This paper proposes the connection of digital twin with blockchain to execute performance-based digital payments. They first present an architecture where they connect blockchain to digital twin and then demonstrate the feasibility of both the concept and technical architecture by integrating the Ethereum blockchain with digital building models and sensors via the Siemens building twin platform.

(Yoon & Pishdad-Bozorgi, 2022) this state of the art is related to the construction supply chain supported by blockchain. This state of the art is important because it investigates the most critical problems of the construction supply chain and identifies how the blockchain can help in these problems.

(Tan et al., 2022) this article aims to analyse how blockchain can help IM to overcome the challenges it faces. The research leads us to understand that BIM and blockchain are able to interact successfully. What they have found is that the interaction of blockchain with BIM has numerous possibilities of use and that some of the problems of BIM can be solved with the help of blockchain.

3.3.1. Summary from the articles

The following is Table 5, which contains information regarding the articles explained above and which are organized based on the main themes they focus on.

Author	Main Subject	Title
(Zhong et al., 2020)	Quality Information Management	Hyperledger fabric-based consortium blockchain for construction quality information management
(Tezel et al., 2020)	Supply Chain Management	Preparing construction supply chains for blockchain technology: An investigation of its potential and future directions
(WANG et al., 2017)		The outlook of blockchain technology for construction engineering management
(Kifokeris & Koch, 2020)		A conceptual digital business model for construction logistics consultants, featuring a sociomaterial blockchain solution for integrated economic, material and information flows
(Yoon & Pishdad-Bozorgi, 2022)		State-of-the-Art Review of Blockchain-Enabled Construction Supply Chain
(Christidis & Devetsikiotis, 2016)	Blockchain IoT integration	Blockchains and Smart Contracts for the Internet of Things
(Kim et al., 2020)	Construction Management	A Study on the Application of Blockchain Technology in the Construction Industry
(Yang et al., 2020)		Public and private blockchain in construction business process and information integration
(Elghaish et al., 2022)		Financial management of construction projects: Hyperledger fabric and chaincode solutions
(Ni et al., 2021)		Blockchain-Based BIM Digital Project Management Mechanism Research

Table 4. Summary of the literature review

Author	Main Subject	Title
(Perera et al., 2020)	Blockchain Applications	Blockchain technology: Is it hype or real in the construction industry?
(Cai et al., 2018)		Decentralized Applications: The Blockchain-Empowered Software System
(Hunhevicz & Hall, 2020)		Do you need a blockchain in construction? Use case categories and decision framework for DLT design options
(J. Li, Greenwood, et al., 2019)		Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases
(Sawhney et al., 2020a)	Construction 4.0	Construction 4.0; An Innovation Platform for the Built Environment; First Edition
(Khalfan et al., 2022)	Procurement	Blockchain Technology: Potential Applications for Public Sector E-Procurement and Project Management
(Zheng et al., 2020)	Smart Contracts	An overview on smart contracts: Challenges, advances and platforms
(di Giuda et al., 2020)		The shortening and the automation of payments: The potentiality of smart contract in the AECO sector
(Hamledari, 2021)		Impact Assessment of Blockchain-Enabled Smart Contracts on the Visibility of Construction Payments Automated Indoor Construction Progress Monitoring Using Unmanned Aerial Vehicles (UAV) and Computer Vision View project Blockchain-Enabled Smart Contracts for Construction Payment Automation View project
(Hunhevicz et al., 2022)		Digital building twins and blockchain for performance-based (smart) contracts
(Liu et al., 2019)	BIM	Building information management (BIM) and blockchain (BC) for sustainable building design information management framework
(Tan et al., 2022)		Potential functionality and workability of blockchain within a building information modelling (BIM) environment
(J. Li, Kassem, et al., 2019)		A proposed approach integrating DLT, BIM, IOT and smart contracts: Demonstration using a simulated installation task

Table 5. Summary of the literature review - Continuation

3.4. Possible Fields of Study

The potential in the construction industry meets some that already exist in the various industries. Based on a bibliometric study by (Xu et al., 2022) the most covered topics were those related to Contract Management, Supply chain Management, Information Management, Stakeholder Management, and Integration with other technologies.

Across the research made there have been three topics that stand out with real applications. These topics are related to Contract and Payment Management with enhancement of Project Management efficiency, related also with Procurement and Supply chain Management, and finally the insertion of BIM and Smart Asset Management.

Here we encounter three problematics to the construction sector that are intended to be resolved with these applications:

- Payment and Project Management – Lack of Transparency
- Procurement and Supply Chain – Lack of Traceability
- BIM and Smart Asset Management – Lack of Collaboration

The problems that are identified in the construction industry, among many, are the lack of productivity and with it the several reasons to this.

4 PROPOSED USE CASES

In this dissertation, the topic to be developed and studied will be the applicability of blockchain technology in the Portuguese construction industry.

To this end, several articles with different proposals and several publications that suggest the application of this technology in various industries were analysed. The construction industry is, as mentioned before, lagging behind the technological advances that we are witnessing nowadays.

The problems that were identified in the research on the sector raised questions about the current functioning of process operations and how they could be improved, particularly with the use of blockchain technology. To his end we shall explore three different aspects and fields of the AEC industry with a generic explanation on how they functionate with and without blockchain technology and the possible gains it may bring, but also if there is any downgrade of the process.

4.1. PAYMENT AND PROJECT MANAGEMENT

According to Paydex, an Informa D&B indicator that assesses the average number of days of late payment against agreed deadlines (August 2020) with suppliers, construction sector pays with an average delay of 25.3 days.

Informa D&B states that the phenomenon of late payments "may become more serious, as a significant increase in operating costs is expected for many companies, as a result of the conflict in Ukraine and the rise in the price of energy".

At the time of writing this thesis, according to the Informa D&B barometer, only 19.2% of companies in the construction sector meet their payment deadlines, with an average delay of 23.7 days. The sectors that can go along with the construction sector also present delays.

The regime under which the industry operates is one of lack of trust between stakeholders, requiring the intervention of intermediaries. The construction industry involves collaborations between different and independent parties with competing objectives. As a result, the arrangement, verification, authorisation, and enforcement of payments depend on centralised mechanisms of trust, such as banks that are important participants in the construction network as intermediaries for value transfers. Different pieces of information need to be verified and cannot be used to automate the transition from progress updates to payments. Banks, as external actors, play a central role in the construction supply chain.

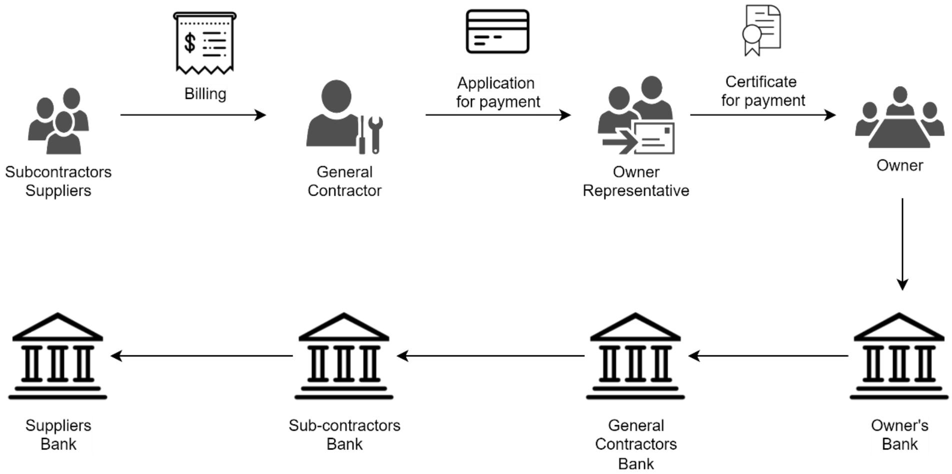

Figure 16. How normal transactions function

Lack of trust makes it difficult to automate payment processes, as parties need to check the validity of facts. Smart contracts offer an opportunity to improve, automate and make more efficient a number of processes. An example of a scenario that could be improved is, a worker enters the construction site using an identification, which he already uses for safety, hygiene and security reasons, whose information is registered on the blockchain including the time he is on the construction site. The blockchain is distributed between the client, contractor, and inspector. This way no extra type of administration is needed to validate the information as it has been registered on the blockchain. On the basis of agreed terms based on the number of hours worked, a smart contract can trigger payment and even send payment receipts to those involved if necessary.

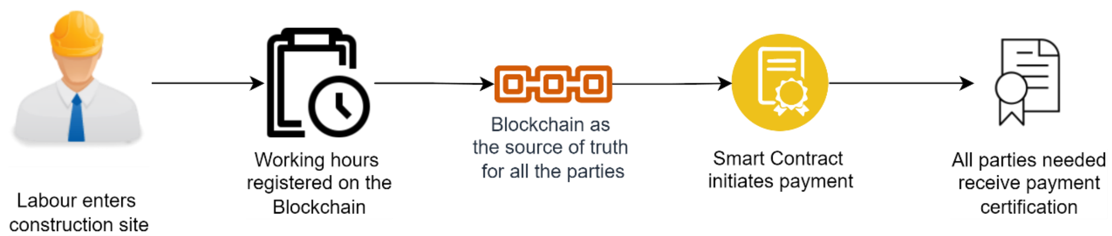

Figure 17. Example of how a labour may be paid ate the end of the day

An important aspect of a smart contract is that external parties or information sources often need to be involved as well. The sources or employees ensure the link between the smart contract and the process it manages. In the example given, this employee would be the one who ensures that the person is well identified based on the time he enters and leaves to avoid that someone else does it for him, being essential to create a system without gaps in information, preventing fraud and avoiding wrong decision making.

This scenario can also be adapted in the planning phase of a project, in the sense that orders for materials and products are defined according to a programme. In other words, in the blockchain platform, there will be milestones to be met that in conjunction with a smart contract are prepared to initiate payments according to timely deliveries or worked hours. These quick and transparent payments would be activated by a smart contract through a blockchain application that could be linked to the project's bank account. Thus, the payment would be made with fiat currency.

In the example to be demonstrated below, we will see how blockchain can enable a commercial alliance between two elements for the design and project phase. This commercial association between two entities involves the sharing of risks and benefits or rewards and is more commonly referred to as joint venture.

To better understand the use case, it will be necessary to divide the interpretation in four parts, Project Planning, Design and Quality Assurance, Delivery, and Project Progress. The blockchain if well implemented brings an output with benefits for each of these parts.

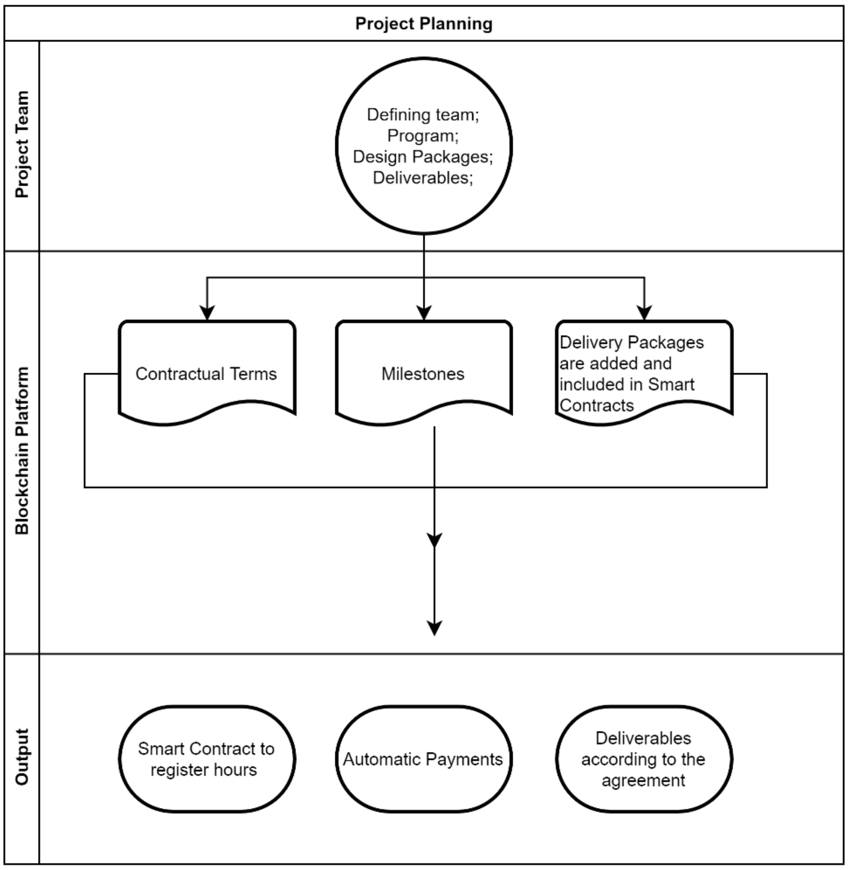

Figure 18. Project Planning

In the part related to project planning the project team defines the team that will intervene, the process program, the design packages, and the deliverables. Then, on the blockchain platform we will find the contractual terms, the objectives to be met and the delivery packages are added to the smart contract. With this connection the blockchain allows the smart contract to record the time, the payments are automatic, and the deliverables are in accordance with what has been agreed.

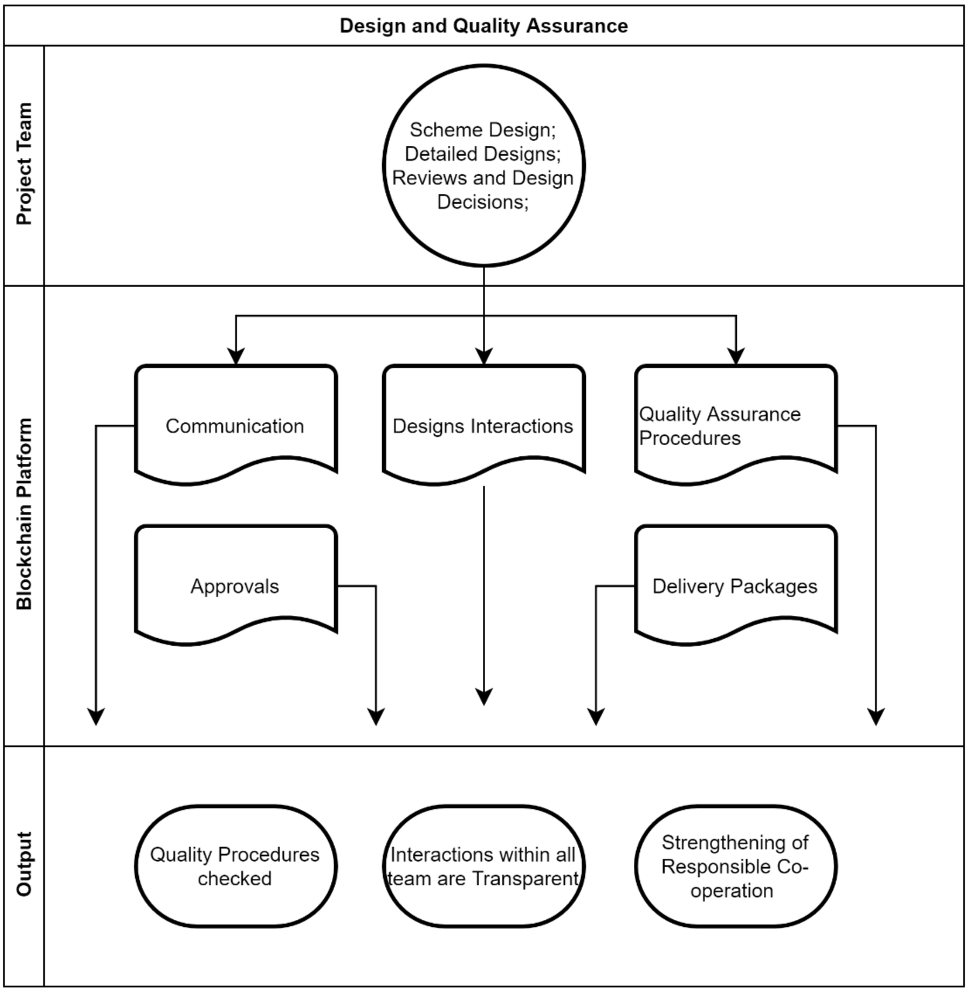

Figure 19. Design and Quality Assurance

In this part related to Design and Quality Assurance, the project team presents the design scheme, including the detailed drawings and also the reviews and decisions related to the design. Next, the blockchain platform intervenes as it allows communication, interaction between the designs, the procedures related to quality assurance are implemented, and the design and delivery packages are defined. Finally, this junction allows quality procedures to be followed, the interactions between the team are transparent, and there is reinforcement of responsible collaboration.

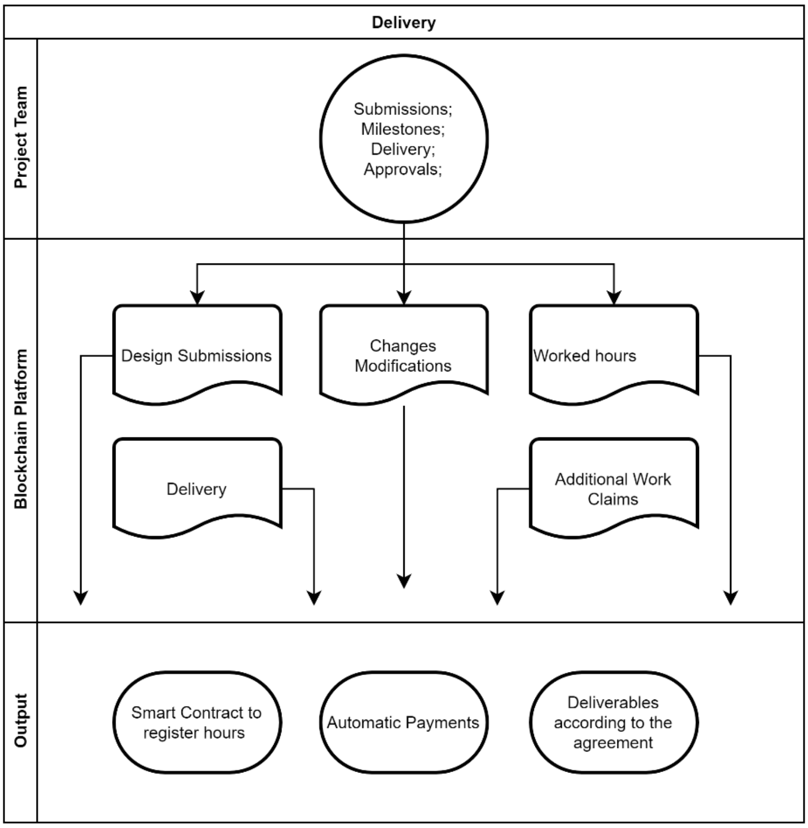

Figure 20. Delivery

In Delivery, the project team commits to making submissions, submitting milestones, and completing deliveries and making approvals. The blockchain platform, meanwhile, records design submissions, modifications, hours worked or deliveries and additional work claims. The output is that design approvals are transparent and there are automatic payments according to the work registered.

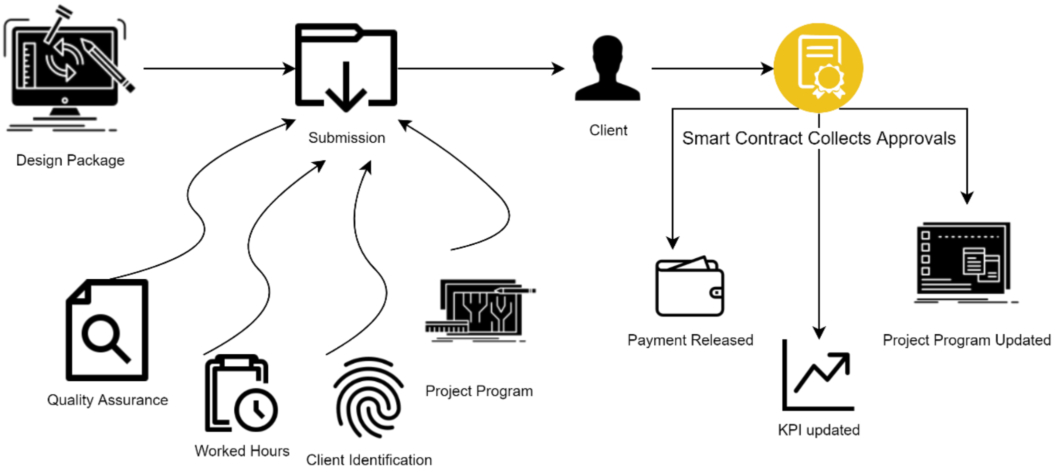

Figure 21. Submission of a design package

Once the design is finished, the document control system can inform the smart contract that a design package has been submitted, stakeholders are notified so they can check the documentation. All interactions are recorded on the same blockchain platform, and payments and updates to the project are then initiated by smart contracts.

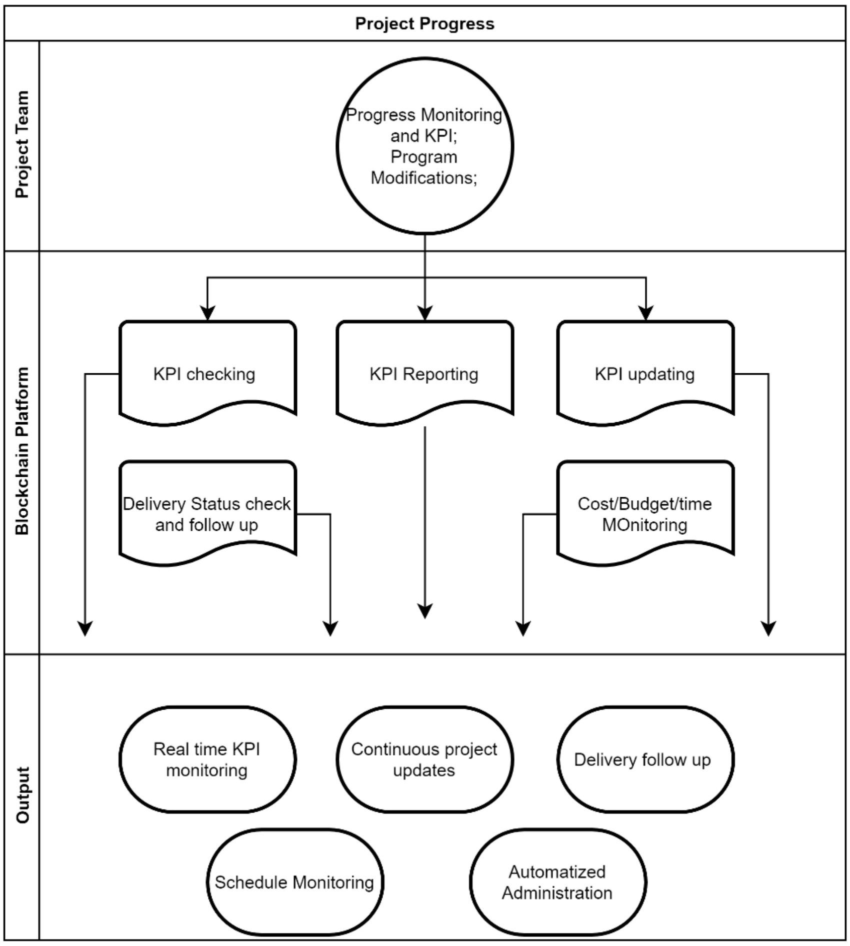

Figure 22. Project Progress

At the project management level, it is necessary to check the progress of the project and as such this Project Progress layer presents the project team as responsible for monitoring the progress and the key performance indicators and ascertaining the modifications of the program. The blockchain enters to facilitate the check up on KPIs, reports and updates them, performs a delivery status check and follow up and allows monitoring of cost, budget, and time. The output of this is that there is real time KPI monitoring, the project is continuously updated, there is a follow up of deliveries and a monitoring of the schedule and the administration is automated.

Through the information being traceable it allows for greater certainty in monitoring progress and estimating cost and time.

4.1.1. Discussion

This topic may be the most controversial of the three to be explained, yet it is not new. In the same way that banks emerged with their current currency and regulation, payment through blockchain may arise. The scepticism that exists around blockchain technology may be the same that has arisen with other new technologies. We say may, because we still lack concrete applications that can confidently sustain its application in the industry.

Nevertheless, through an application of the kind proposed is the beginning of a different point of view towards payments and project management with greater transparency. The idea has possibilities, but it will be very difficult to overcome the challenges that lie ahead.

The possibilities include reducing payment delays, disputes, and preventing small companies from being disadvantaged by large companies in terms of payment deadlines. This translates into a more reliable industry.

The difficulties are that there is a lack of will to change what currently governs, a lack of will to discover new methods to help the management of the work and project in order to improve small processes, among others.

Via smart contracts, back-office processes can be automated with the aim of improving efficiency and complying with the terms agreed. The benefits include cost savings, as the costs of a project can be better controlled.

In short, the application may one day be implemented, but it requires a number of steps to be taken before it can be put into practice, from legal issues to be resolved to industry acceptance.

4.2. Procurement and Supply Chain

Productivity problems and the economic significance of a supply chain are two reasons why there is discussion about improving the supply chain in construction. According to a report by McKinsey Global Institute, one of the seven areas that construction should take action is procurement and supply chain. Better planning and transparency between agents as contractors and suppliers would have a significant impact on reducing delays (Barbosa et al., 2017).

Supply chain is defined by (Salhi & Christopher, 1994) as ‘the network of organisations that are involved, through upstream and downstream linkages in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer’.

The construction supply chain consists of the supply chain of materials, labour and equipment and involves various stakeholders, such as owners, architectures, engineers, general contractor, subcontractors, and various suppliers. A typical construction supply chain is demonstrated in Figure 23.

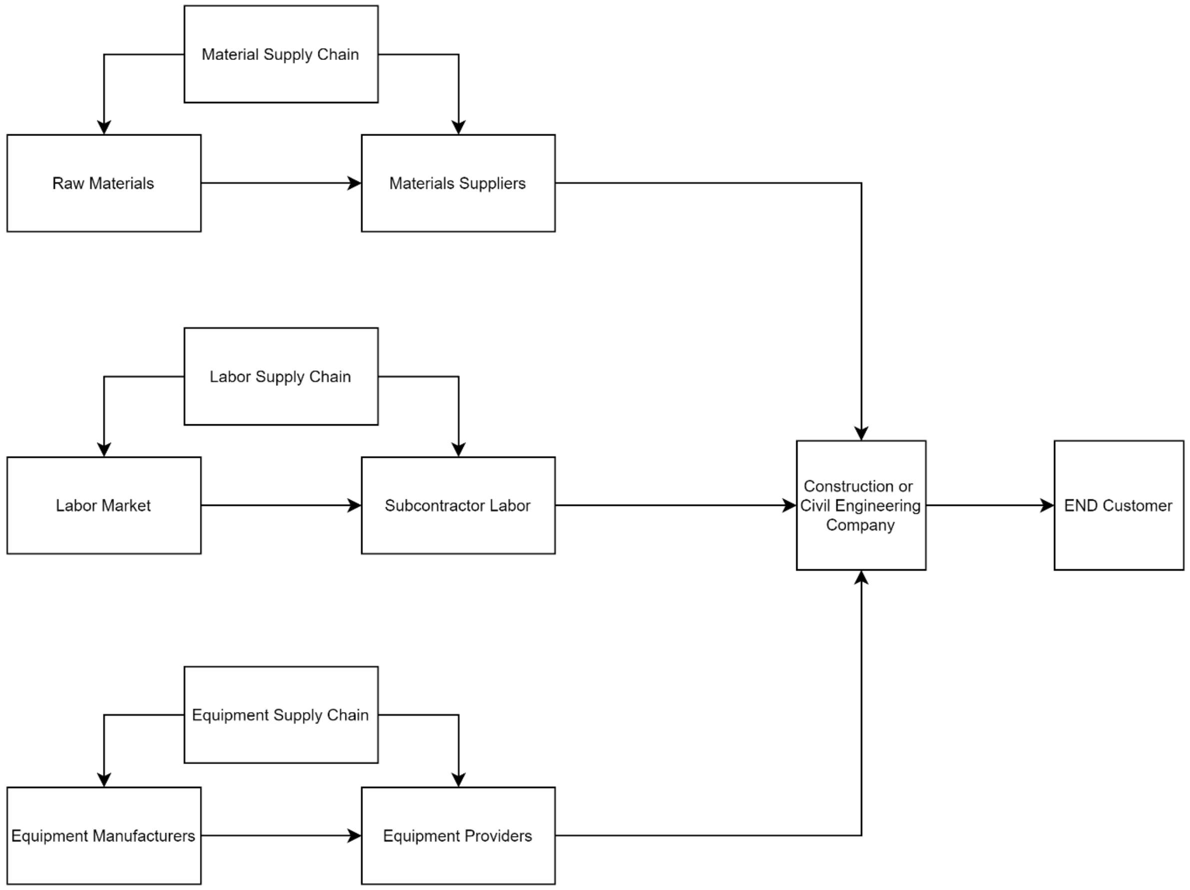

Figure 23. Typical Construction Supply Chain

There has been a growing interest in supply chain management in construction. This interest arises with the intention of understanding and characterising the problems and finding solutions to better coordinate this extensive chain. The aim is to reduce the storage of raw materials and equipment, make more advantageous purchases, rationalise transport, eliminate waste and add value to the final product, which is the project itself.

(Vrijhoef & Koskela, 2000) characterises the supply chain in construction as:

- The construction site ends up being the epicentre of production, where materials are routed, causing the construction supply chain to converge on that very site.
- The construction supply chain is unstable as each construction site is temporary, immobile, and unique, so its production requires repeated reconfiguration of separate project and design organisations.
- Construction is built to order, "make-to-order", as there is no stock, since each project corresponds to the design of a new product, making them unique. This characterisation may not correspond to all construction works, as in some constructions there is a certain level of repetition in materials and processes, as is the case of houses or residential buildings.

The recent study of (Yoon & Pishdad-Bozorgi, 2022) suggests that there is a correlation between critical issues in the construction supply chain and the impact areas of blockchain, which is demonstrated in Table 6.

Construction Supply Chain Critical Problems	Impact Areas of Blockchain
Green Supply Chain Management and Sustainability	Sustainability
Collaboration and Integration	Collaboration and Integration
Information Sharing	Information Sharing
Tracking of Materials Logistics	Supply Chain Traceability and Trackability
Counterfeiting	Anti-Counterfeiting and Product Authenticity

Table 6. Supply chain critical problems and the corresponding areas where blockchain may aid

A problem that exists today is related to Construction and Demolition Waste (CDW), since the construction sector presents an intense consumption of raw materials. The construction sector is responsible for a considerable percentage of waste produced in Portugal.

The implementation of a Circular Construction model to prevent the production of CDW is fundamental for the sector's transition to a Circular Economy. This concept applies to the entire supply chain. Architects, engineers, and contractors have the role of ensuring that the design of buildings takes into account the reuse of materials used. (Smart Waste Portugal, n.d.)

The blockchain appears as a solution as the registration in this type of system is very useful to certify all the parameters and qualities of the materials in order to improve the control of what is used. Moreover, even for the future events such as rehabilitation or demolition, a detailed identification of the materials is very useful to fight against waste or correct maintenance of a building.

Blockchain with its transparency and trackability characteristics brings numerous advantages to the stakeholders of a project. For example, a blockchain system makes it possible to identify a certain material and see its registration and traceability throughout the supply chain until the construction. A stakeholder such as the project owner will have access to the materials purchased, as well as production certificates, quality, and other certificates, and to the transportation to the construction site. Any stakeholder will have access, at any point of the supply chain, to the immutable records made on the blockchain. This record ensures confidence in the quality, specifications, and standards of the materials.

The blockchain with its process traceability feature makes the supply chain easily traceable, so the control of time and delivery conditions and other tasks become easier, faster, and less bureaucratic. A framework of how it may work is exampled in figure 25.

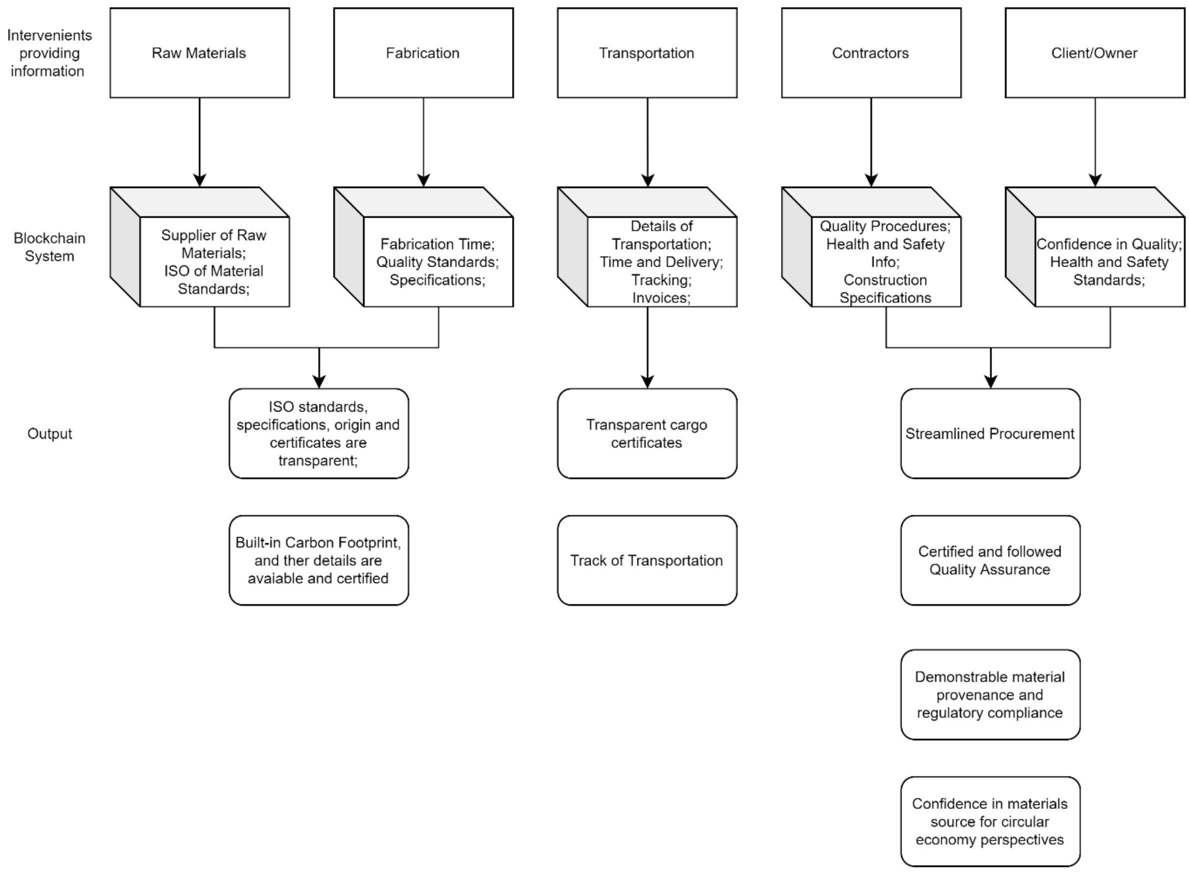

Figure 25. Framework of how blockchain may enable a better trace of information in a construction supply chain

The industry gains traceability, reducing waste and improving material rationalisation. Manual documentation is reduced and since they are tamper-proof, digital approvals can govern the movement of goods. As information and documentation is shared on the blockchain, the blockchain through smart contracts, can manage invoicing and authorise payments as soon as certain previously agreed terms and conditions are met.

4.2.1. Supply Chain Simplicity

What usually happens in a segment of a supply chain is that from the moment the suppliers are chosen, and the purchasing order is issued by the general contractor, the order is issued by the suppliers who request the approval of the delivery by the contractor. If this approval is denied, then the order is renewed and if it is accepted, there is an authorisation for transportation and delivery on site. Then transport and delivery itself takes place. Once the goods arrive on site a series of checks are carried out, such as quality. If the checks fail the orders are renewed and if they are approved the issue of invoice is requested. The invoice is then sent to the suppliers and then processed by the contractor who requests payment from the client. At the end, after the payment has been processed, it is released to the suppliers.

However, to simplify this process, (Kifokeris & Koch, 2020) suggests that independent logistics consultants intervene by deploying a blockchain solution. A blockchain solution offered by independent logistics consultants can be implemented on the economic flow involving the customer, the general contractor, and the suppliers. It increases the transparency and traceability of the entire supply chain segment since it involves all the intervening parties in the consignment process, in particular the placement, approval, and renewal of orders, which can all be done on the blockchain. It should also be noted that, with this proposed solution, the successful on-site checks of the deliveries are codified and stored, the issuing of the invoices are triggered, and the payments are released.

The proposed solution has a similar look to the flowchart shown in the figure below:

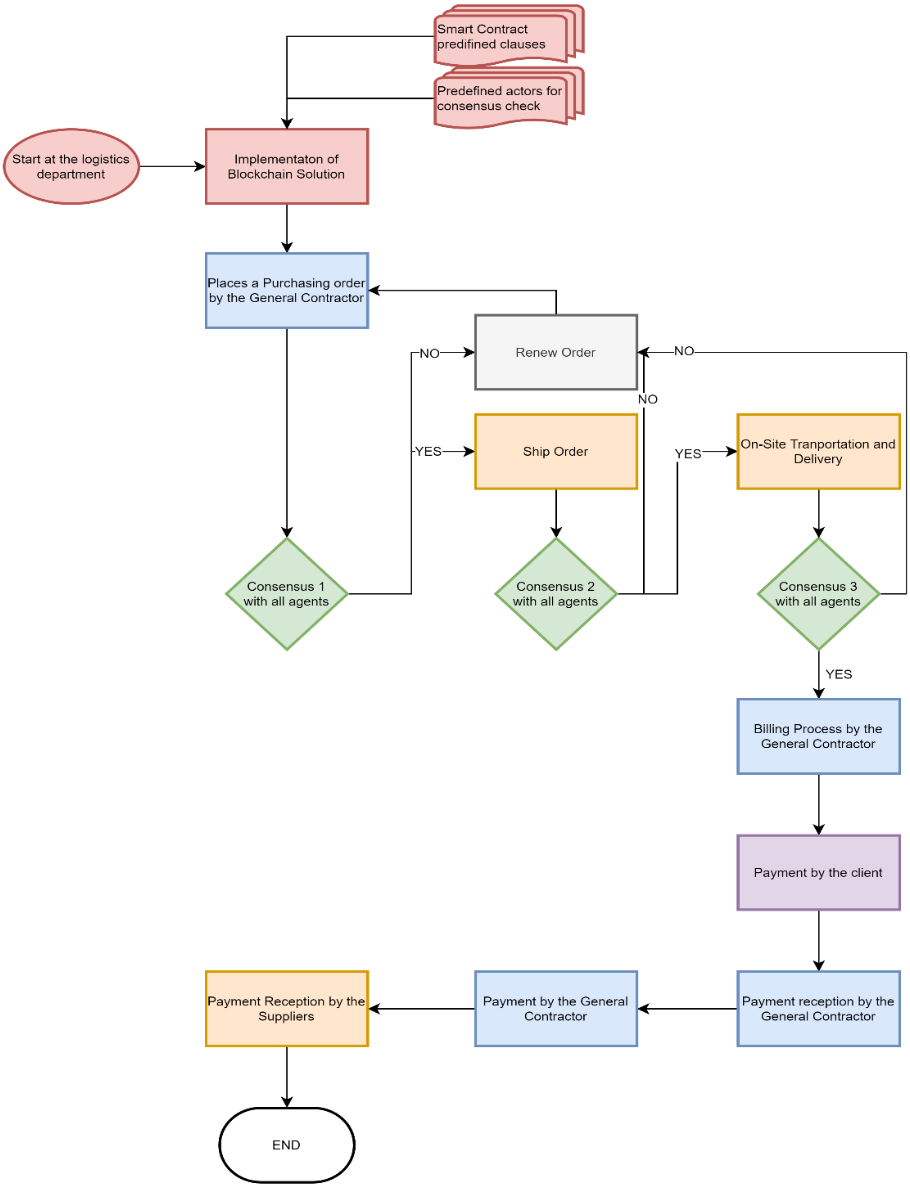

Figure 26. Supply Chain segment simplification through Consensus

4.2.2. Discussion

This proposal is one of the most relevant today, as we already have practical examples of the functioning of a supply chain through blockchain in other industries, which are explained in chapter 3.1. Blockchain can reduce the fragmentation and complexity of large projects. The fact of being able to allocate information about materials in the blockchain, enabling a continuous record, free of erratic changes, allows to have confidence I the origin of materials, which consequently reduces waste and ensure a better quality of the built element, as well as guarantees that those responsible for any change are known. The predictability can increase with respect to the procurement phase, since the need, the product specified, and the quantities are better known.

This way, the supply chain of a project can be largely improved and the predictability of a project increase, reducing the time lost with these processes, not to mention the time lost with the search for documentation, which is often a recurring problem.

4.3.BIM AND SMART ASSET MANAGEMENT

In the past decade there has been an increase in interest in the optimisation and automation of construction works, through the use of tools and technologies such as BIM. BIM offers construction professionals, engineers, and architects' tools to facilitate planning, design, construction and management of building and infrastructures. BIM should not be limited to generating 3-dimensional models where only the physical aspect of the work is analysed but should evolve and be able to contain the total information of a project and its documentation, such as orders, invoices, and payment records.

Blockchain is able to complement the use of BIM with confidentiality features, provenance tracking, disintermediation, non-repudiation, multiparty aggregation, traceability inter-organizational recordkeeping, change tracing, data ownership, among others. (Turk & Klinc, 2017) Blockchain emerges as a way to address this matter with solutions, as it is a technology that allows an accurate audit of who makes some kind of modifications, when these alterations are made and what they are. In a blockchain network, information is uploaded and compiled into the immutable blocks. This information, as it is in interconnected blocks is constantly being verified on a peer-to-peer network by other block users in the blockchain. As the information in the blockchain cannot be tampered with without the knowledge of other users, it is possible to have greater trust and transparency in this ledger. Therefore, the blockchain fulfils the same purpose that BIM is intended for which is to be a secure source of information.

The integration of smart contracts in this sector requires a basis such as BIM. The advances in this software allow the use of information from the project to be later compared with the execution, to verify payments. The concept and the will exist, the only thing missing is for the technology to overcome its limitations, namely at a legal and regulatory level, in search of delivery of a totally reliable product. (Mason, 2017) Both BIM and blockchain, despite performing different functions, are governed by the fact that they are two reliable information storage technologies. The highly complex projects undertaken require a series of detailed and complete information in order to facilitate understanding on site.

By complementing BIM information with blockchain technology we are creating tools with the aim of increasing responsibility and quality in the industry. BIM has the ability to combine the information coming from blockchain as:

- Supply Chains information
- Provenance of materials
- Payment details

It also has the ability to transmit information to the blockchain. This is then used in smart contracts to initiate actions, such as payments or purchase of materials.

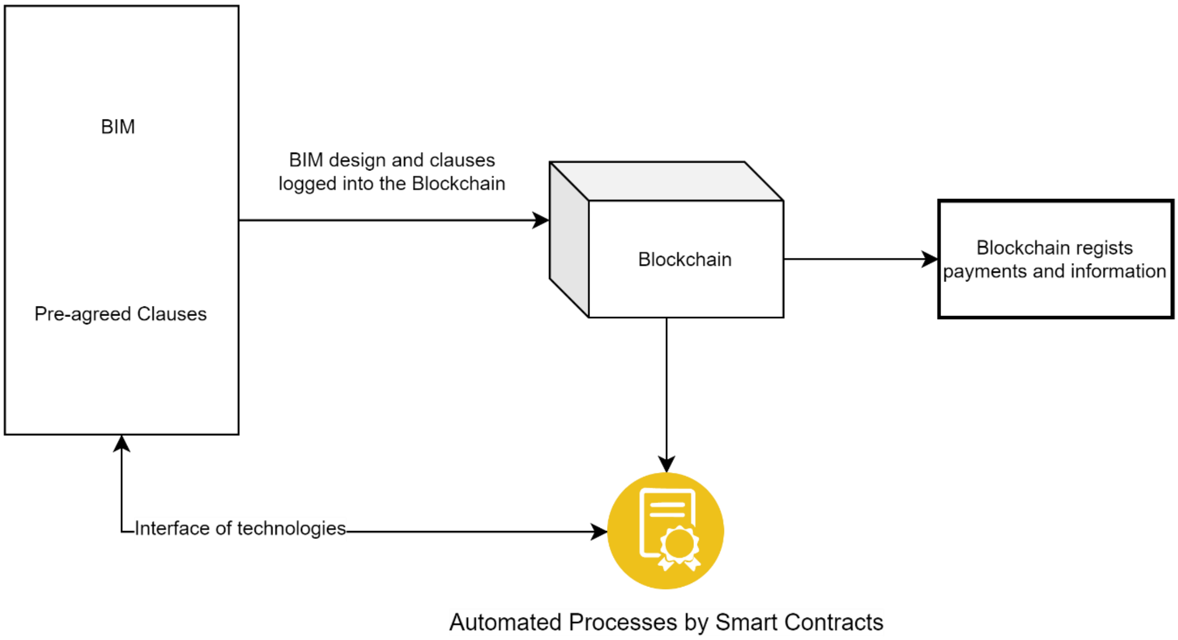

Figure 27. Interface between Smart contracts and BIM through Blockchain

In the model, the blockchain will work as a basis to strengthen the projects carried out in BIM. Since all decisions and actions are recorded and can be consulted, we are, in this way, ensuring greater confidence between entities. By recording data such as:

- Graphic decisions related to the appearance of the building
- Consultation of content
- Registration and consultation of payments and transactions

The actions performed within the platform are recorded through a log in. All actions can be consulted, as well as the consequences they have. These properties help to eliminate the lack of trust and increase the security of the businesses, seeking to guarantee an increase in productivity and quality of the constructions. With the regularisation and optimisation of the payments we are motivating both entities so that the contracts are fulfilled as stipulated, and the transactions are made as expected.

A benefit that can be considered is the fact that decisions are inherent to the system presented. In other words, the consensus checks that are made between the intervenient of a project are made in the system reducing the delay of a process. As said before, the information that can be put in a blockchain, such as decisions, procurement, among others, and connecting it to the BIM model, we can ensure the existence of detailed information about who made a change and what it was in a safe and immutable record. The environment that is created is one of trust, because it is easier to identify those responsible for changes to the project, reducing disputes.

An important aspect to mention is the possibility of using blockchain to ensure the intellectual property rights of a project, which prevents the erratic use of a model by someone who is not the author. Blockchain ends up bringing in a collaborative environment the guarantee of who brought what to the project.

A problem that exists in relation to BIM is the need for updates in order to have an overview of the development of the construction. These updates are often difficult, as access to the construction site is often not easy, in order to make these types of checks. (Bulent Yusuf, 2020) one way to update the

BIM model is with the help of the IoT in conjunction with the blockchain. For example, the update of the BIM model during the construction phase of a beam does not happen in real time. The process ends up taking much longer than expected, since it is often necessary to use sensors to verify its proper implementation at the level of its position and even resistance. A practical way to exemplify the interaction process is as the figure below represents.

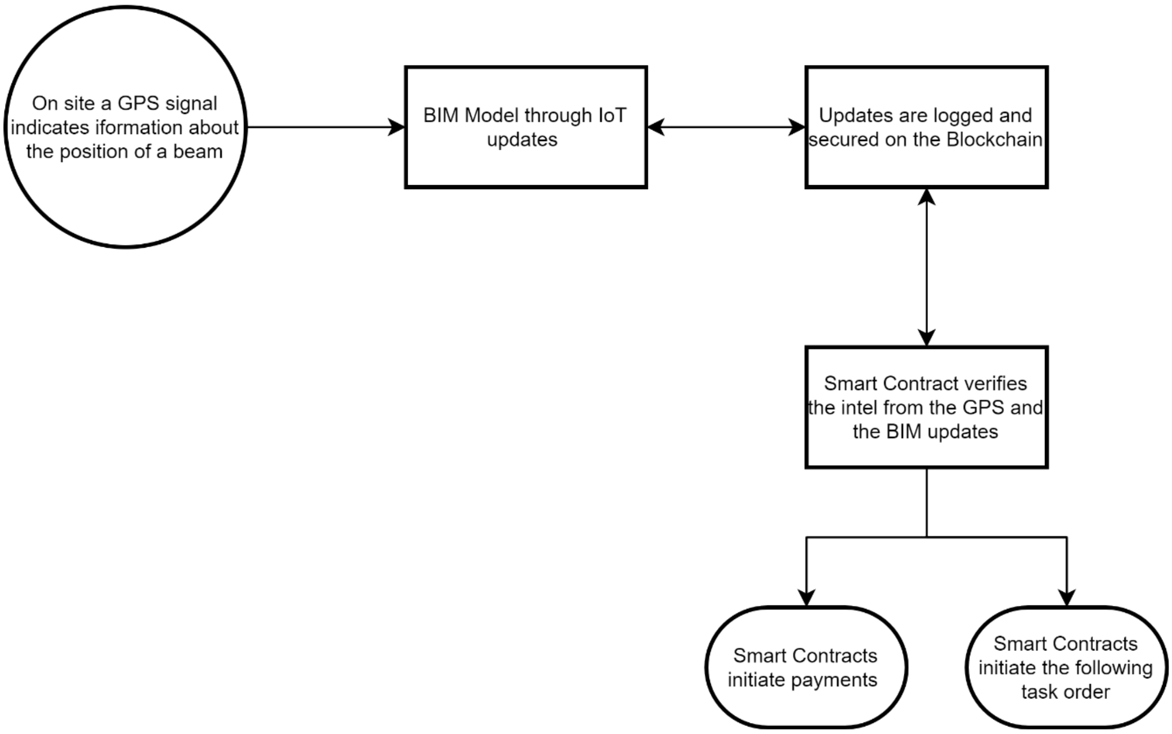

Figure 28. Interaction process between BIM IoT and Blockchain

What the scheme helps to interpret is the use of the two systems to help update the BIM model. In other words, a sensor, in this case a GPS signal from the beam transmits information to the model about its position so that it can be updated in that same virtual model. This information is then put into the blockchain where it is cross-referenced with the smart contracts that verify the information that is, the information from the GPS signal and the BIM model update. As soon as these verifications are approved, the smart contract enables the release of payments for the task in question and prepares the system for the next task, in this case the next beam.

The advantages of this hypothesis don't end here, since this information collection could be updated throughout the lifetime of the building. This framing of BIM with blockchain would bring several advantages in the possibility of creating a circular construction, insofar as the data relative to the asset would be secure. The materials would be easily identified at the manufacturing level, in case of what was explained in subchapter **4.2.** This is useful, because the identification of a material from its origin and even during its use phase would give us the possibility to evaluate its condition in a better way. This condition would then be assessed in order to, if necessary, proceed to its replacement, repair or maintenance. These procedures would be carried out in a more direct and coherent manner since we would have all the necessary information at our disposal.

4.3.1. Blockchain-supported digital twins enable smart asset management throughout the life cycle

A digital twin is a virtual model that is created with the intention of reflecting a physical object. It assumes the use of sensors to capture an up-to-date condition of the object. These sensors translate information about performance, condition, temperature among others. This information is then transmitted to a processing system and applied to the digital copy. This virtual model can, once it has the data, make simulations, and create scenarios where there may be improvements that can then be applied to the real object. (IBM, n.d.-c) Digital twin is a necessary tool to contextualise insofar as it is useful to use for asset management.

Good asset management requires the use of the most efficient means to achieve the best performance from the respective asset. (Designing Buildings, 2021) Blockchain, BIM and digital twin can operate in coordination, for a better asset management as the following scheme translates.

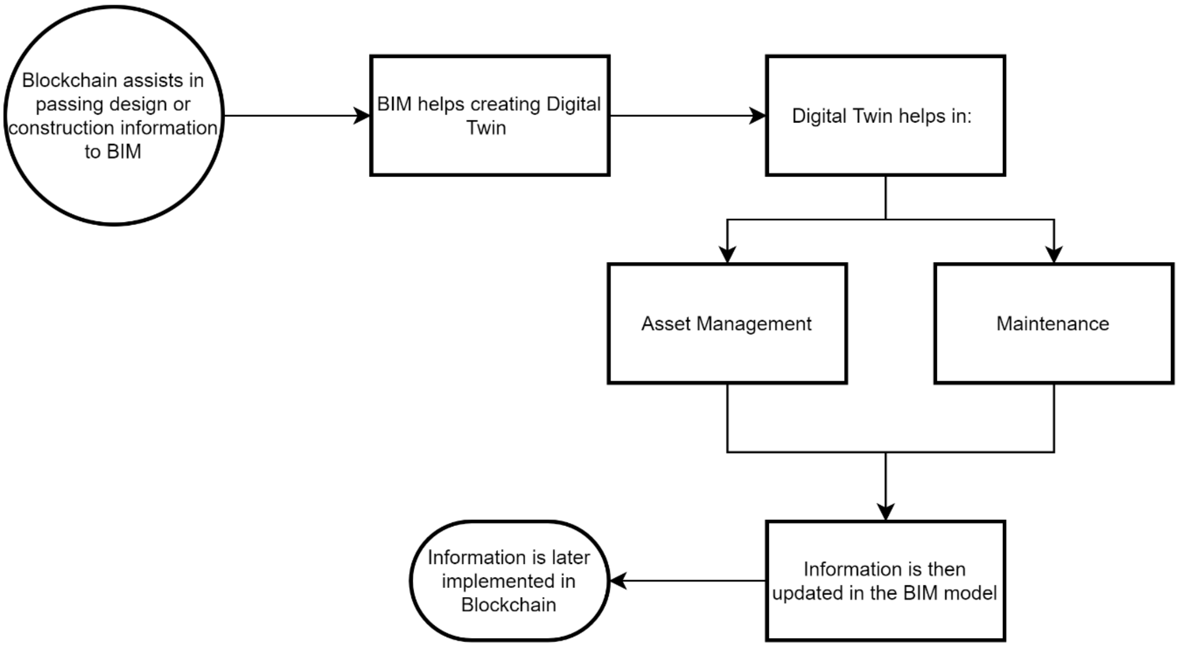

Figure 29. Operation between BIM, Digital Twin and Blockchain

Using blockchain, the digital twin would contain the information that helps define operational strategies at the maintenance level and would also have access to the continuous traceability data record. If a part of the structure were to fail, the digital twin would be able to identify the element presenting the defect and also the person responsible for its assembly and procurement.

This would have advantages in terms of reducing insurance problems, as the time lost in identifying the responsible and the specific problems would be reduced. It would also bring greater pressure on those involved to do a better job, as responsibility would always be quickly identified.

IoT could intervene with the interconnection of devices that would translate the information referring to several aspects. Through the interconnection of these technologies the vision that we would have of an asset would be close to a reality updated to the minute. This vision could be accessed by all authorised parties through the blockchain.

4.3.2. Discussion

The combination of BIM and blockchain is one of the most researched topics at the moment. This is because it is believed that blockchain can elevate the capabilities that BIM offers. This can be seen in chapter 3.3., where articles discussing the collaboration of the technologies are presented.

In conjunction with BIM, blockchain can create a single source of truth for all aspects of a project. As we intend to demonstrate, this model can be a digital twin of an asset that helps by giving support to design and construction, but also to operation throughout the asset's lifetime.

Blockchain has the potential to solve the challenges that affect the use of BIM. BIM can contain information on materials and elements through the use of blockchain and can also submit information on design changes that can then be used to make payments pr orders through a smart contract. This makes exploring this combination of technologies very interesting and its possible applications should be further explored.

5 CONCLUSIONS

5.1. GENERAL CONCLUSIONS

The civil construction sector has a vast legacy of constraints and deficiencies that have been alleviated with the investment of technological advances in the sector itself and with the adoption of more advanced and automatic technologies in the procedures and ways of working. The development that we are witnessing today is increasingly more innovative, however, the construction industry has been showing a tendency to lag behind on these new innovation mechanisms. One reason that may be important is the fact that the construction sector is an industry that experiences a resistance to change, since it has in its essence a mentality that what is done nowadays does not need to be changed. The implementation of construction management mechanisms is fewer than those found in other AEC specialties, and therefore there is waste and incompetence in the processes adopted.

Given the delay mentioned above, the industry is willing to evolve and part of this transformation involves being digital. With this in mind, with the emergence of several innovations, blockchain technology has also emerged, which is one technology that is gaining reputation and should be studied more. This technology shows great potential in solving and mitigating problems that affect the sector.

The development of this thesis has shown the growing interest in the technology in the different industries, with special attention to the studies that have begun to be made with the aim of modernising the construction industry. The challenge of this dissertation was to present methodologies that could be adopted as a response to current shortcomings that have been prolonged and persistent over time. The study made it possible to propose three more relevant uses in the area and to gather factual deductions regarding their application.

The collected state-of-the-art proved to be quite positive, as relevant definitions on the technology in its more theoretical context were gathered, being essential to understand how it works. The technology continues to be studied, so its definition in relation to its uses may not yet be completely defined.

The study done regarding the different industries was very useful to understand how the technology is used and, so, some conclusions were drawn about some examples that can be transported to civil construction. Next, the articles read were essential, because through them it was possible to base the proposal and also the state-of-the-art. These articles presented some distinct approaches and most of them presented more proposals than concrete examples. The proposed methods of use were based on all the study presented before, so they are proposals of use for the Portuguese industry in order to evaluate the possibility of being effectively implemented. The technological advances regarding this subject are still very late, and in the Portuguese case they are even later. This is due both to the lack of investment, but also the lack of willingness to investigate new alternatives to the methods used today.

The industry may show some resistance in the evolution of these studies, and more practical cases are needed to prove the efficiency of the technology, because it is through practical case studies that it will be possible to sustain the evidence that the technology may or may not work. The objective of this thesis is to be a first step in the in-depth study of this technology, with the next step being to put into practice one of the proposed examples and compare the current mode of use and the sustained mode of use through blockchain technology.

The objective of this dissertation would be, in fact, to present an example of application, however, due to the reasons listed above, the company where the thesis was carried out did not have in its possession an application model and is still investigating the state-of-the-art of the technology and if there is benefit or not of using blockchain in construction. This last point is where this dissertation is inserted. The fact that the company in question is lagging behind in terms of use proves the delay mentioned. The study of the application is still very embryonic, so in the Portuguese case it is even more so.

5.2. DIFFICULTIES ENCOUNTERED

The challenges throughout this dissertation were extensive, since moments of stagnation arose due to the fact that the thesis has changed direction halfway through. In other words, as previously stated, initially the thesis was going to have a practical component that led to a study at the programming level that, however, proved to be unnecessary, since there was no need for it, once the company did not present support at the level of knowledge regarding blockchain programming to the point of creating an application that could be used and tested. This proved to be a huge setback, since the practical approach had the need to disappear and thus a component with theoretical proposals emerged.

The approach to this theme by the scientific and academic community of the sector is relatively scarce, which makes it difficult to carry out the work. Due to this, it was necessary to spend a considerable amount of time to familiarize with the basic concepts and the research done was more extensive due to the need to identify relevant and current content. The fact that in our community it is still a fairly recent theme, makes the collection of knowledge somewhat more difficult.

5.3. PROPOSALS FOR FUTURE DEVELOPMENT

The dissertation, which culminates with the proposal of three use cases, foresees improvements to them, insofar as only with a practical development will it be possible to draw precise conclusions as to how they work. The theoretical idea has a scientific basis, so if it is well founded and proposed, it may show great possibilities, however, as mentioned, it will be necessary to start tests where it is possible to compare the traditional way of operation with the proposed way of operation.

The studies on this theme are starting to increase and the interest is starting to emerge and have more relevance in the more technologically developed countries. Being, also, an objective of this dissertation to investigate the use of blockchain technology in the Portuguese construction industry, a study should be conducted on the distribution of money from the RRP. This is because, being one of the points of the RRP the commitment to the digitalisation of companies, it should be considered whether it is worth to dispense money to encourage the use of blockchain in the industry.

In short, the developments that can be made are based on the practical application of the technology, as blockchain technology is new and there are a number of hurdles to overcome. However, the potential to improve the industry is too great to ignore. With construction being one of the largest industries in the world, productivity, and the infrastructures it creates are concerns that should be the target of major investment. There is a responsibility to improve the digitalisation of the industry and prepare it for the challenges of the century ahead.

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