# A study on the implementation of digital technologies for improving steel reuse

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**Master Thesis**

# A study on the implementation of digital technologies for improving steel reuse

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# EXECUTIVE SUMMARY

Introduction & Scope

The goal of this study is the enhancement of circular economy in AEC industry and more specifically the focus is on reusing elements from steel structures. To achieve that and taking into consideration that construction sector is one of the least digitalized industries, a framework incorporating three different technologies for improving information management is suggested. Specifically, tools such as BIM that are already in practice and constantly gaining ground in the industry are deployed for this job. At the same time, two other technologies, sensors and blockchain are adopted, which are mainly embraced in other industries but their potential to add value in AEC projects has recently become evident by several studies. In order to fulfill the above-mentioned scope, the following main research question was formed.

- ***How can digital technologies (BIM, Blockchain, sensors) enhance the reuse of steel elements?***

Current problems

Currently the poor application of digital technologies especially during the early phases of a project such as the design phase has led to insufficient information over structural elements and in our concern steel elements. This is mainly to the established traditional CAD modeling concept which lacks storing any kind of information apart from the dimensions of an element. In addition to that problem comes the absence most of the times of an organized database which would gather all the necessary information that the task of reuse requires. That creates an information gap when a structure reaches its end of life since no data about the elements exist. For that reason, several intermediaries, such as fabricators, material dealers, service centers etc, have to be involved. This increases the complexity of the business plan since it raises the budget and requires extra time and effort. For example, if no information is known then the elements have to be transferred to a fabricator to conduct several destructive or non-destructive tests to discover their characteristics and condition. Thus in the majority of cases, reuse ends up being not a viable financial option and being inferior compared to using recycled or new elements. In an attempt to make reuse a more viable option, the scope of this study, as it is seen in Figure i, investigates the course of steel elements through the phases of design and construction as well as operation maintenance through the spectrum of information management.

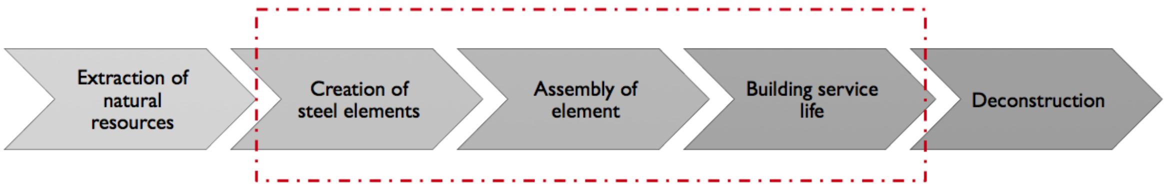


Figure i. Parts of steel element's lifecycle that would potentially be enhanced by the present study.

Research design

The study is based on the Design Science methodology suggested by Wieringa (2014) and Johannesson & Perjons (2014). In short, Design Science is based on a design cycle which is an iterative process consisting of three main steps, (i) the problem investigation, (ii) the treatment of the problem and (iii) the validation of the problem. The part of treating the problem is addressed by proposing an artefact. Artefacts are defined as tools developed by people to constitute the mean of solving problems or improving situations. They can have many different expressions, from actual physical objects, to information models, programmes or conceptual frameworks, methodologies, guidelines etc. In the present study it will have the form of a framework.

Findings

Having identified the problems and the stages where the lack of proper information management affects reuse, chapter 3 lays the theoretical background of the proposed technologies while chapter 4 answers the main research questions and describes how BIM, sensors and blockchain can potentially enhance the process of reuse.

Starting from the design and construction phase there are several information directly related with steel elements which should be registered from an early stage. For that reason BIM is deployed as a necessary tool that would assist not only to have a clear 3D representation of the structure, and consequently of the steel elements, but also to form a database where all the related information would be stored. More specifically, it was firstly examined and then suggested which properties of steel elements as well as which relations among them or other components, could be of a help. Those are summarized below and their contribution is explained in more detail in chapter 4.

- Material properties
- Types of steel element
- Capacity
- Type of connection
- Assembly sequence
- Location

The second suggested step of this study is the creation of a secure, transparent and immutable database to store data during the service life of the structure. This would be achieved by introducing two technologies. First, the sensors which will monitor certain characteristic elements, for example the exterior ones or those that structural design analysis urges, and second the blockchain technology which will be the operating system where the monitored data would be stored. This supplements the data registered in the design and construction phase described above, and would contribute in creating a complete profile for each element.

# CHAPTER 1 – INTRODUCTION

*The first chapter is an introductory one, it starts with an overview idea of what is circular economy which is the ultimate objective of this study. The first subchapter gives its definition while it explains the main difference from a linear model. Moving on to the second subchapter, circular economy is examined from steel's perspective and more specifically by stating the differences between reuse and recycle. Finally, a short description follows regarding the current problems that a reuse strategy is facing.*

## 1.1 CIRCULAR ECONOMY

It is reported that over the last decades, the Construction Industry is responsible for the exhaustion of significant amounts of natural resources. During the 90s, this amount was around 40% (Rees, 1999), while nowadays it has slightly dropped to approximately 32% (Yeheyis et al., 2013). Apart from that, in some countries, like Canada for example, the Construction industry has been responsible for the production of 25% of the overall municipal solid waste (Yeheyis et al., 2013).

Wastes have been produced throughout the life cycle of projects, even through the earlier phases of a project like planning and design phase, due to inadequate waste management (Esa, Halog & Rigamonti, 2016). However, the end-of-life is the most harmful phase generating more than 50% of the total wastes of a construction project (Kibert, 2008). To this contributes the lack of reuse potential (Akanbi et al., 2018).

To address those issues, two are the most promising solutions, the sustainable development and the circular economy (Sauvé, Bernard & Sloan, 2016). Sustainable development is development that meets the needs of the present without undermining the ability of future generations to meet their own needs (UN. Secretary-General and World Commission on Environment and Development, 1987). This aims at reducing the carbon emissions and the use of raw materials as much as possible in order for a project to achieve a better carbon footprint. However, there are limitations to this method, mostly because optimizations of the design are not feasible to be done. Furthermore, Sustainable Development is still related to the linear economic model, which by itself adds more drawbacks to its implementation (Pomponi & Moncaster, 2017). Thereupon, other options like Circular Economy have to be considered.

In this aspect, the present study will enhance circular economy by analyzing what characteristics of steel's lifecycle can get improved. Steel structures can be considered as extremely circular products since, at a very high percentage, steel elements of a structure are being recycled after their end-of-life. However, there is still room for improvement regarding the reuse of steel products. In the following paragraphs the concept of circular economy will be described while in the next subsection it will be specified around steel.

The idea of Circular Economy intents to delivering new products by avoiding the use of new raw materials (Sauvé, Bernard & Sloan, 2016). Its main principle, as it can be seen in Figure 1.1, is to create a closed loop of the flow of materials, by implementing recycle and reuse techniques of the waste products (Korhonen, Honkasalo & Seppälä, 2018; Pomponi & Moncaster, 2017).

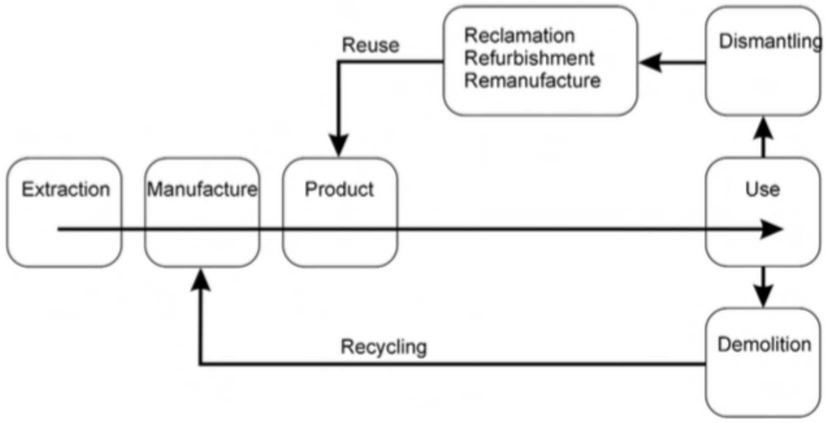


Figure 1.1. Closed loop life cycle of materials (Addis, 2006)

In contrast, with the linear economic model, Figure 1.2, where the main idea lies in extracting the raw materials from the environment, then create the construction materials and put them together to form the construction in a way that after its end of life it cannot be decomposed and thus it becomes obsolete (Mangialardo & Micelli, 2018). For that reason, attempts are being made to disengage from constant exploitations of natural resources and consequently drop the linear model and shift to a circular model with the aid of reuse/recycle techniques as well as an improved supply chain management. In that case, circularity would bloom (Pomponi & Moncaster, 2017).

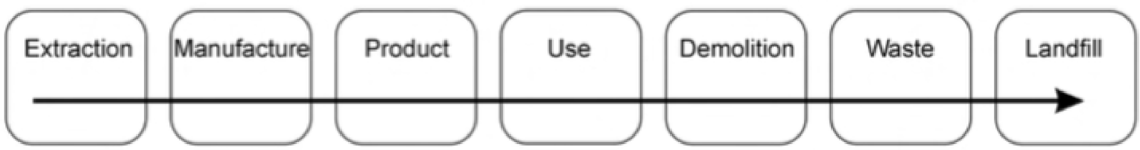


Figure 1.2. Linear life cycle of materials (Addis, 2006)

Kirchherr et al. (2017) in their attempt to provide a definition for Circular Economy discovered that there is not an universal definition since it is a subjective notion and depends on the people using it. For instance, it is used differently in China than in Europe. In China, they use it to solve environmental issues arising from industrialization and fast growing pace, while in Europe it is seen as a business opportunity and it focuses on the reduction of waste and the extraction of raw materials (McDowall et al., 2017).

Up until this time, it has not become clear who was the first that established the notion of Circular Economy (Winans, Kendall & Deng, 2017), however it is believed that it was inspired by a mixture of ideas from different fields, like ecological economics and industrial ecology (Korhonen et al., 2018). Pearce and Turner, two economists, were among the firsts who presented the idea of Circular economy during 1990. They conducted a research about how the 1st and 2nd law of thermodynamics could shift from a linear to a circular economic model (Sarkis & Zhu, 2018). Furthermore, in 2008 China was the first country that enacted a law concerning Circular Economy, while in 2010 The Ellen MacArthur Foundation was founded, one of the most important institutions regarding Circular Economy (CIRAIG, 2015).

There are different suggested strategies that could support the Circular Economy model and they are usually concentrated in a, so called, R ladder. In the literature, a lot of different alterations of the R ladder can be found, from a 3-R to a 10-R ladder (Reike, Vermeulen & Witjes, 2018). One of the most classic contains, recycle, refurbish, reuse and reduce while a more complete one, introduced by PBL agency (2019), is illustrated in Figure 1.3. As it can be seen, it contains 6-Rs, with the strategies higher in the list requiring fewer resources and those at the bottom more (PBL, 2019). Moreover, the last two, Recover and Recycle, are considered the least preferred as in some cases Recycle for example may lead to production of even higher emissions than the original product would require (Korhonen et al., 2018).

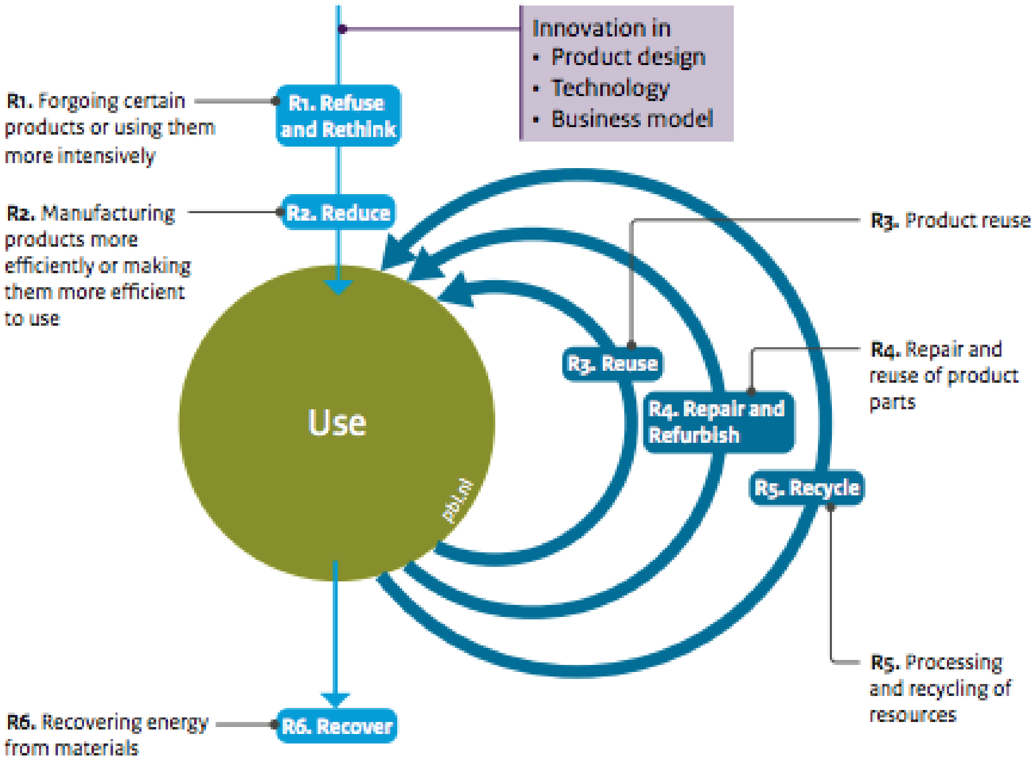


Figure 1.3. 6-R Circularity Ladder (PBL, 2019)

A more desired option and the one that this research will examine, urges reusing steel components. After a building's end of life, materials can play the role of a material bank and used in new buildings, retaining a closed loop among the components (Hopkinson et al., 2019). Though, achieving a completely closed loop is not considered realistic due to the entropy law and dissipation (Naustdalslid, 2014). In addition, those ideas require further development of the existing knowledge and tools as well as greater participation of the industry (Lacy & Rutqvist, 2015). That is even more intense in the construction industry where each project is unique, large supply chains are involved, complexity is growing and new technologies take a lot of time to be adopted (Pomponi & Moncaster, 2017).

## 1.2 Steel Circular Economy

Steel reuse can play an important part in a global strategy for the efficient use of materials (Allwood et al., 2011; Allwood & Cullen, 2012) as the carbon and energy embodied in structural frames can represent up to 20–30% of the assumed 50-year life-time carbon footprint of a building (Nadoushani and Akbarnezhad, 2015; Dimoudi and Tompa, 2008). In most studies, only carbon emissions that stem from energy spent in operational aspects (like lighting, heating etc.) are considered, however that is inaccurate because it does not include the emissions produced due to the embodied energy in building materials and construction (Dunant et al., 2018; Choudhary, 2012; Ley & Samson, 2003). In that aspect, strategies to reduce the embodied carbon and energy rely on the choice of structural materials (Nadoushani & Akbarnezhad, 2015). Steel as a structural material prevails by far concrete, which has been almost completely exploited and leaves very little room for improvement (Dunant et al., 2017). In contrast, steel can save carbon emissions and energy by applying recycling or reuse as alternatives to demolition (Milford, 2010).

Steel in theory, is considered to be a 100% recyclable material and has the unique characteristic that it does not lose its properties after it has been recycled (World steel, 2012). Nevertheless, after melting the steel, environmental impact still remains since substantial CO2 emissions are produced and sometimes it exceeds the benefits of recycling (Georgakellos, 2006; Bior, 2008). Additionaly, drawbacks regarding delays have been observed due to difficulties of manufacturing management and time-consuming scrap processing (Fujita & Iwata, 2008).

On the other hand, a reuse strategy only requires energy for deconstruction, transportation and possible repairs, leading to considerably lower environmental damage (Kozai Club, 2001). Steel is slightly affected by aging, mainly from rust and plasticization in areas where large scale earthquakes occur, yet, both these aspects can be overcome. Rust can be removed and steel members be painted again while plasticization can be avoided with a proper design which allows steel to maintain its elastic properties after an earthquake (Wada et al., 1998). Figure 1.4, presents the negative environmental impact of using new steel elements created by recycled ones compared to reclaimed steel element.

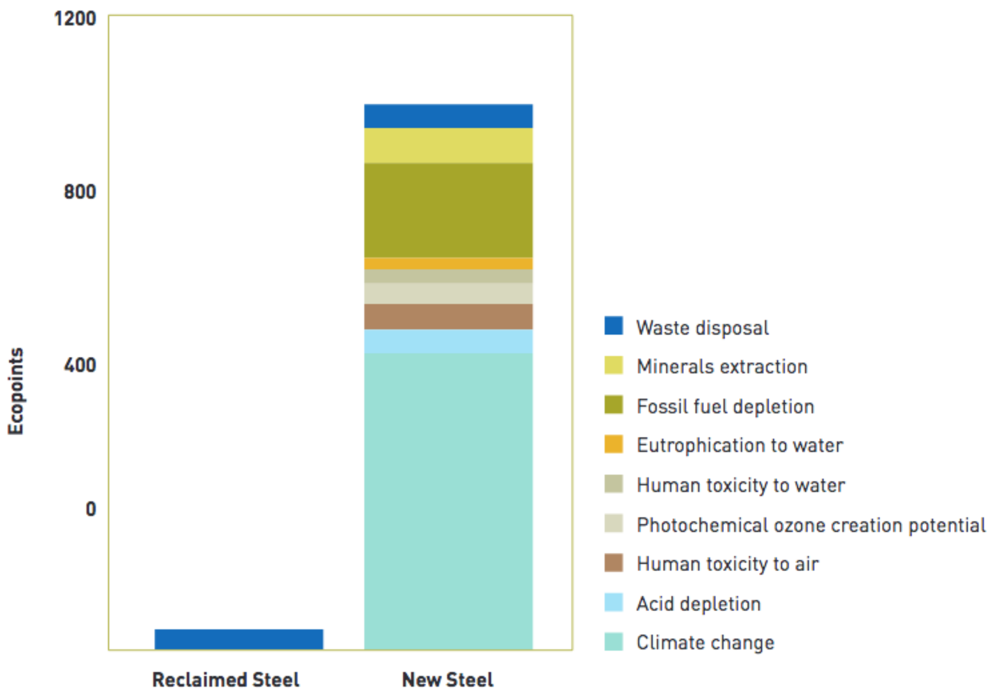


Figure 1.4. Environmental benefits of reclaimed steel vs new recycled steel (BioRegional, 2008)

Structural steel sections constitute the ideal candidate for reuse since they are rigid and dimensionally fixed elements which are connected together with bolts or welds to shape structural assemblies. Those assemblies are deconstructable with relative ease after the end of life of a structure and, as opposed to the current common applied practice of recycling by melting the old steel (Sansom & Avery, 2014), they can be reused. Studies by Cambridge University (Allwood et al., 2010) and Toronto University (Gorgolewski et al., 2006) reveal that reusing happens more often in the U.S. and Japan, where buildings have shorter life time, rather than in European countries, where buildings are used for a longer period of time and several materials might encounter fatigue.

## 1.3 Problem Statement

Construction industry is regarded to be a hazardous industry while it is responsible for more than one third of global emissions (Ness et al., 2015). At the same time, around half of the produced steel is deployed in the AEC and generates emissions of around 7 per cent (Ness et al., 2015). Moreover, it is considered that AEC has the potential to reduce its emissions more than any other industry. To that end, European Union and other organizations push, with measures and standards, for an increased circular economy in the future years (EEA, 2021). However, in our case, the reusing of steel elements, despite the willingness of organizations and individuals, there are practical barriers that hold back its application.

In-short the main problem is that new or recycled steel costs less than reused steel. That is because reused steel involves costs regarding a potentially further processing as well as costs for more complex logistic procedures. Furthermore, there is uncertainty regarding the quality and the properties of the elements since there are no reliable data stored. Even if there are some, the lack of traceability, to know the history of the building, does not safeguard warranty of the elements to the stakeholders. Hence, several intermediary actors, like fabricators, material dealers and service centers will be involved to assess if elements are suitable for a reuse by subjecting them to destructive or non-destructive tests. With this however leading to an expansion of the business network and raise of the total budget and environmental burden.

Part of the above problems are rooted in a more generic issue of AEC and that is the slow adoption of digital technologies and the limited R&D which is less than any other industry (Lewis, 2020). Although, there are tools that have already been used, like BIM, their capability to store information is not fully exploited towards reuse. On the other hand, there are other technologies, like IoT and blockchain, which are thriving in other industries and according to researchers can add value to AEC in general and to reuse (Ness et al., 2015; Bertin et al., 2020). Figure 1.5 shows which parts of a steel element lifecycle currently have poor information management and would be attempted to be enhanced by the present study.

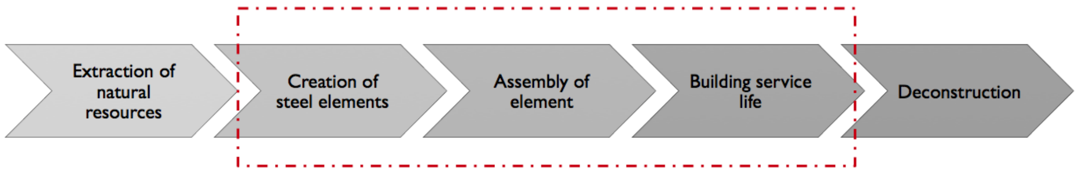


Figure 1.5. Parts of steel element's lifecycle that would potentially be enhanced by the present study.

# CHAPTER 2 – RESEARCH DESIGN

*This chapter outlines the main scope of the study, it involves the research questions as well as the methodology that is selected to answer those questions.*

## 2.1 RESEARCH OBJECTIVE

The main incentive for this study is todays urge for providing more circular solutions in order to unburden the environment from the linear way of operating the last many years. Hence, the underlying objective of the study has to do with circular economy in the steel sector. What would be attempted to achieved is to promote reuse of steel elements to a level that would be comparable with recycled and new elements. That would be accomplished by proposing a framework which gradually enhances information management during the different phases of a project and ultimately lead in creating of a "passport" of the steel elements of a structure after its end of life.

## 2.2 RESEARCH QUESTIONS

Setting the research questions would better orient the objective of the study while answering them would lead to having gathered all the necessary information for the final result of the study. The research questions consist of a main question which expresses the main objective of the study and several sub-questions which act supplementary to the main research question and gradually aid in reaching the final outcome of the study. The main research question as well as the sub-questions are presented below.

Main research question:

- ***How can digital technologies (BIM, Blockchain, sensors) enhance the reuse of steel elements?***

Sub-questions:

1. *What is the current steel reuse situation?*

2. *Which symbols, symbol properties and relations between symbols in a typical BIM model contain usable information for this task?*

3. *Which additional information should be collected in the lifecycle of a building (possibly attached to the BIM symbols)?*

4. *How can the above information be safeguarded with blockchain technology?*

## 2.3 RESEARCH SCOPE

This study tries to promote circularity in steel structures by attempting to further incorporate technologies like BIM, Internet of Things (IoT) and Blockchain in the AEC industry. BIM is already applied in construction projects but not yet focused on aspects which will enhance reusability of steel structures. IoT and blockchain on the other hand, are implemented with success in other industries and according to researchers have the potential to add value to the AEC industry as well. Firstly, the current reuse practices, the involved actors as well as their problems are described and analyzed. Then a framework is developed, proposing which information should be included in each phase of a steel element's lifecycle by integrating BIM, IoT and blockchain technologies for improving the reuse process.

## 2.4 RESEARCH METHODOLOGY

The selected methodology for this study is the Design Science which is analyzed by Wieringa (2014) and Johannesson & Perjons (2014). Design science can be undertaken for different kind of studies, from a large scale research conducted by a group of researchers and last for long time to a small scale one which will be concluded in a short period of time by a single researcher. Design Science methodology is defined as a scientific way to address practical or general interest problems by developing and applying artefacts (Johannesson & Perjons, 2014). Artefacts are tools developed by people to solve problems or improve situations. They can have many different expressions, from actual physical objects, to information models, programmes or conceptual frameworks, methodologies, guidelines etc. There are plenty of different forms that an artefact can have with all of them be under a common way of interaction with the problem's context and eventually its solution or improvement (Johannesson & Perjons, 2014; Wieringa, 2014). What cannot be designed in the context of artefacts is people, values, fears, norms etc. Those notions are part of a problem and should be examined but they cannot change (Wieringa, 2014).

The basic principle that stimulates a researcher to start a design science methodology is the identification of an insufficient or problematic process that can be improved by its application. When this becomes explicit then the context of the problem should be framed and described in detail (Wieringa, 2014; Johannesson & Perjons, 2014). That way the artefact can be designed accordingly and add value in the process. When the artefact is developed a validation process should follow to review if the initial requirements have been fulfilled (Wieringa, 2014).

What is more, Gregor & Hevner (2013) categorize design science into four different types according to artefact's contribution. For example, it can be a completely new solution to a completely new problem or a repurpose of an existing solution targeting a different problem. Figure 2.1 summarizes the four different types and shows in a red circle under which type this study belongs. As it can be seen, it is characterized as an improvement research which means that it will enhance an already existing solution or suggest a new one. It is also the most common type as well as the most challenging one, because it has to prove about its usefulness over the existing solution.

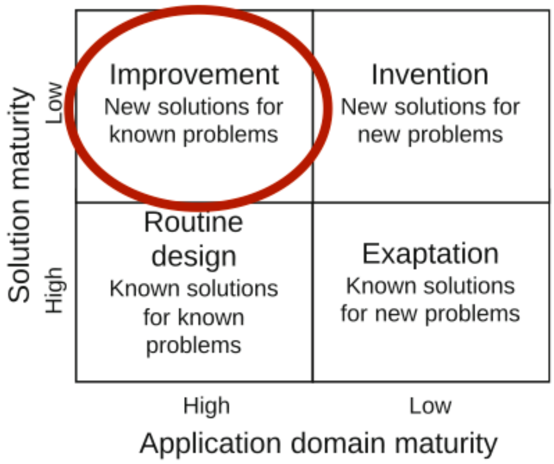


Figure 2.1. Artefact's different types of contribution (Gregor & Hevner, 2013)

Wieringa (2014) describes the design science methodology through the design cycle. Design cycle is an iterative process that consists of three steps. The first step is the problem investigation, the second is the treatment of the problem and the third one is the validation of the proposed treatment. Starting with the problem investigation, it examines which parts of the process need to be fixed or improved and why, the treatment phase is where the artefact for "treating" the problem is designed and in the validation phase the artefact goes through inspection to verify whether it "treated" the problem sufficiently.

Subsequently, Wieringa presents an extended version of the design cycle, the engineering circle (Figure 2.2). Engineering circle is comprised of the design circle plus two more steps. Hence, after the treatment validation there is the treatment implementation and the implementation evaluation. Treatment implementation is actually the application of the artefact; it is being tested to the respective problematic process. While implementation evaluation rates how successful the "treatment" was and even define if a new iteration circle is required. In Figure 2.2 all the steps of the engineering and design circle are displayed along with some suggested questions that needs to be covered in each step.

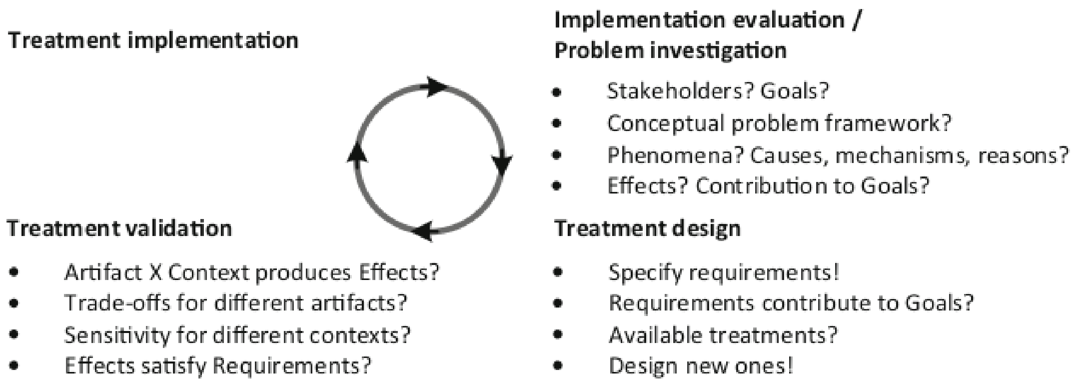


Figure 2.2. Engineering cycle (Wieringa, 2014)

Johannesson & Perjons (2014), describe design science methodology similarly to Wieringa's engineering circle but with the addition of an extra step before developing the artefact. That is called the "requirements definition". In the requirements definition, a description of the actions to be addressed by the artefact is outlined. This contributes to the resolution of the problems, explained in the previous step, "explicate problem". Figure 2.3 illustrates an overview of all the steps. Despite they are depicted to be in a sequential order, they work in an iterative manner allowing alternations in every step of the process. At the end, according to the evaluation results it is decided whether the artefact is efficient or whether they repeat previous steps in order to improve it.

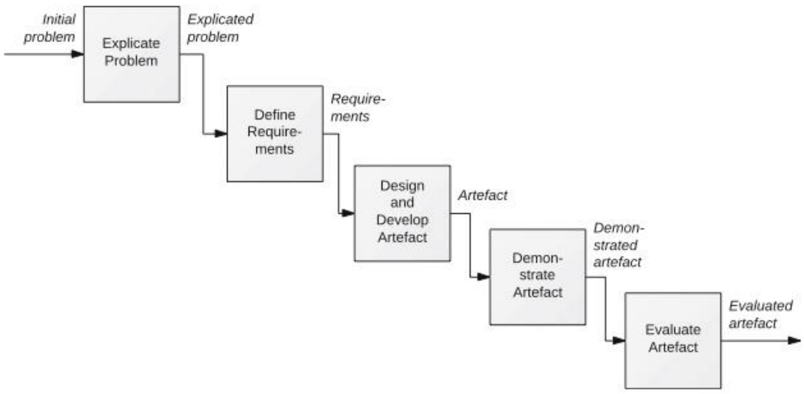


Figure 2.3. Overview of Design Scientific Method (Johannesson & Perjons, 2014)

Furthermore, it has to be noted that many studies do not undertake all the steps of the methodology, they might focus on some of the steps and give less or no attention to the others (Johannesson & Perjons, 2014). For example, a characteristic one and the one that is closest to this study is the requirement-oriented research. This type is giving more weight on outlining and explaining the context of the artefact and not in its application and evaluation.

Apart from the aforementioned, Peffers et al. (2007) as well as several other researchers have analyzed and suggested the design research methodology for improving a process. There might be slight differentiations among them, but the main context is the same. This study will be conducted based on the design circle of Wieringa and the requirement-oriented design research by Johannesson & Perjons. The main difference lies in the last step where instead of a full-scale implementation on a real project and then an evaluation of that, a validation procedure will take its place by conducting expert interviews. Below are summarized the applied steps for this study:

- Exploration of the problem
- Artefact requirements
- Development of the artefact
- Validation of the artefact

Starting with the exploration of the problem (in chapter 3), the current state of reuse as well as its types will be described. Then the weak points of the existing system would be identified and investigated in regards to information management. The method used for collecting the data was by studying old cases where reuse was applied as well as by studying documents i.e. academic publications, books, organizational reviews

(Johannesson & Perjons, 2014). At the same time, the requirements of the proposed “treatment” (BIM, blockchain, sensor technology) are introduced and their background is analyzed through a literature review. In the next chapter, chapter 4, each requirement is further elaborated to ultimately form a guideline of actions which will eventually enhance the process of steel reuse. Hence that will be the artefact of this study. The research will conclude in chapter 5 where the validation will take place. There, the validation procedure is explained and then the outcome of the semi-structured interviews with the experts is presented.

# CHAPTER 3 – THEORETICAL BACKGROUND

*This chapter is divided into three sections. At the beginning, a background of BIM, radio frequency identification and blockchain technology are presented. Those are the central part that is going to be used in chapter 4 in order to achieve the objective of this study, to enhance steel reuse. After that, a description of the current situation is given, by mentioning all the involved actors as well as by explaining the typical steps of a reuse procedure. The last section explains what are the problems that currently limit steel reuse.*

## 3.1 BACKGROUND ON BIM, RFID AND BLOCKCHAIN TECHNOLOGIES

### 3.1.1. BUILDING INFORMATION MODELING (BIM)

*What is BIM?*
According to US National Building Information Model Standard Project Committee BIM is described as *"a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition".*

There is a misconception that BIM is the depiction of the building in a three-dimensional geometric model and this is because in CAD technology the design was two-dimensional. Architects believe that if they work in 3D geometry, it means they are working in BIM. The different way of working and the change in the established work practices of the companies are considered obstacles in the adoption of BIM. Most engineers do not understand that BIM is a continuation of CAD and that if they apply it, they are not doing something very different, they are just using different tools and a more specific methodology. What BIM introduces is the 3D visual representation of the functions of the building (not only the geometry), while with various tools it organizes all the actions and information required for the realization of the project. In this way new dimensions are introduced in the construction (Figure 3.1) such as the 4D, which represents time and the 5D, the cost, the 6D, energy analysis and the 7D, the management of the building.

However, this is a controversy issue among AEC's scientific society since it is not clear what the dimensions beyond 4D represent. Based on the symbolic character of BIM Koutamanis (2020) suggest that higher than 4D it cannot be accountable as dimension. Nevertheless, other functions which are inserted as properties to symbols can be helpful but cannot be called as dimensions.

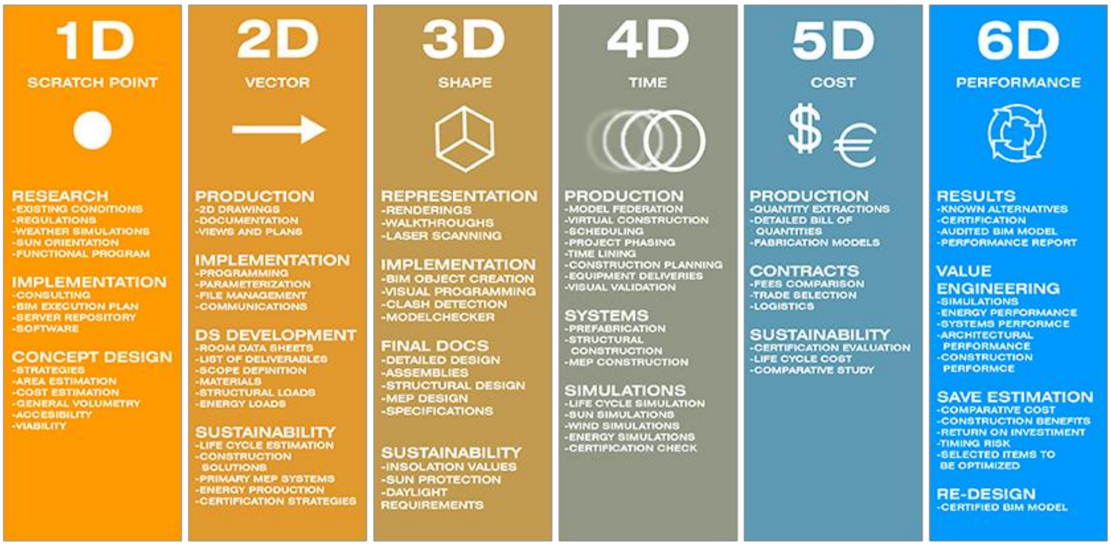


Figure 3.1. BIM dimensions (Vijayeta, 2019)

*Industry Foundation Classes (IFC)*

The AEC industry has many actors that interact with each other: contractors, architects, civil engineers, MEP engineers, public authorities, suppliers, clients, etc. This means high requirement for communication and continuous data transfer (construction plans, design changes, details for construction, certifications, material orders, work progress reports, etc.). Usually each project team uses different types of software and systems than the others, and therefore the processing of the data requires the re-entry of the information received from the other project teams from the beginning into the system of each team. This results in long delays and errors in the exchange of information. The aim is therefore to avoid these problems and to improve the speed and reliability of this process. In this context, a new term has emerged in recent years, called Interoperability, and expresses the ability to collaborate between software and systems of different types such as, architectural, structural, scheduling software, costing and other applications, which allow automatic and reliable data exchange.

Interoperability in the construction sector is a very critical issue, as there are many types of software and different vendors. Much effort has been made internationally to develop standards to ensure the interoperability of digital models produced by the various software. To solve this issue, IFC is developed.

To understand exactly how the IFC standard works, one must consider that the different groups of engineers use different computer programs, which support their designs and produce the digital models of the project, such as e.g. architectural, structural, mechanical, electrical & plumbing etc. When a team sends its model to another team to use it as a background or to supplement it, the information is converted and stored in IFC format so that it can be read by the software of the other application. An IFC file can only be processed and read by another software to transfer the information contained in the digital model of this application and ultimately to the overall project model (Figure 3.2).

Figure 3.2. Interoperability among actors by using IFC

### 3.1.2. Blockchain

Blockchain is a relatively new technology based on the idea of decentralised networks and Distributed Ledger Technology (DLT). It is established by the combination of three different concepts, (i) peer-to-peer protocols, (ii) private key cryptography and (iii) the blockchain's protocol program (Sivula, Shamsuzzoha, Helo, 2018; Hamida, Brousmiche, Levard & Thea, 2017). Blockchain was first developed for supporting the Bitcoin cryptocurrency. It was in 2008 when Satoshi Nakamoto (alias) released an eight page whitepaper describing what is Bitcoin and its supporting system, the blockchain. Bitcoin was the first application of blockchain which allowed financial transactions among the participants without the need of an intermediary third-party like a bank. This is a main difference that separates blockchain platforms from traditional centralized ones.

Traditional databases are governed by a central authority which grants permission to the participants for read, write and modify the databases. In contrast, in blockchain databases there is no central third party administrator and all the data are distributed, possessed and accessed by every participant of the network (Bauerle, 2018). This provides transparency which enhances collaboration among the participants and diminishes the potential of fraud.

Blockchain is a ledger of digital transactions where each transaction is represented by a block. Each block has certain characteristics, that is: the block index, a timestamp which is the date and time that the transaction took place, the data of the transaction which can also be a link, a hash which is a unique number that is its personal identity and the hash of the exact previous block. Each transaction generates a block and each block is linked with the next block forming a chain of blocks, thus the name blockchain. The first block in the chain is called genesis block. More specifically on how it works, there is a peer to peer network, peer is also called a node, where all the peers of the network are equal to each other. All the nodes are connected with each other on a flat topology, with no central administration or central server making the network purely decentralized. In order for the network to assess which transactions (and therefore blocks) are valid and should be recorded to the network there is a consensus mechanism that validates each transaction. If the transaction is approved by the consensus mechanism and recorded to the network, then the entire network will have a copy and access to that transaction.

A consensus mechanism refers to using an algorithm to accept or decline transactions. There are many consensus algorithms with the most common one being the Proof of Work (PoW). PoW is the most used in public blockchains and especially around 75% of the cryptocurrency market uses that one (Perera et al., 2020). However there are many more consensus algorithms such as: Proof of Stake (PoS), Proof of Authority (PoA), Delegated Proof of Stake (DPoS). For instance the most common consensus mechanism, PoW, works by solving complex computational processes and calculating the hash values with a specific pattern like for example leading zeros. This process is called mining and the first node who will do this validation is called a miner and gets rewarded for their work by the system. When the miner validates a block then he shares it with the rest of the network to get verified by the majority of the other nodes. Which consensus mechanism will be applied is predefined among all the involved participants before the creation of the network.

This structure and the hashing algorithm, where only new entries can be added to the chain, means that data in older blocks cannot be tampered. If someone attempts to change an older block then the hashes of that block as well as all the blocks until the latest one will also have to change. However that is not possible due to the consensus mechanism of blockchain. In order for such a change to be implemented it has to get consensus from more than 51% of the nodes that participate in the network. That means that the majority of ledgers should get replicated in a short period of time which is not realistically possible. Hence, immutability is guaranteed since transactions cannot be changed or reversed once the block has been added to the blockchain. The only operations allowed are create and read.

Blockchain technology has two types, it can be either public or private. Public or permissionless blockchain is an open network where anyone can become a member, have access to read all the transactions of the blockchain as well as create new ones. There is no concern or danger about the openness of the network since the consensus mechanism secures the reliability of the transactions and the data. The miners validate and confirm each transaction and only the validated transactions are presented to the rest of the nodes. Then only if the majority of the nodes confirm the transaction it will be added to the public ledger. The most well-known public blockchains are the Bitcoin and the Ethereum which both use a PoW consensus mechanism. Furthermore, they require high computational power to run and maintain the network which also leads to high energy consumption. Digiconomist (2018) mentioned that public blockchains consume around 0.33% of the world's electricity.

On the other hand, private or permissioned blockchain is a closed network where only authorized or preselected members can participate. Private blockchains are smaller scale than public and not all the members have equal rights. Some can access all the transactions while others may have limited access. Similarly, some may have a limitation in adding new transactions and only have the right to read. The role of each user of the network is pre-decided prior to the creation of the network. Private blockchains use the

Proof of Authority (PoA) consensus mechanism which gives the authority to only certain predefined nodes to validate and add new transactions to the network. Because of their smaller scale and different consensus mechanism than those of the public, they require less computational power hence they are faster and they consume substantially less energy.

*Applicability*

Blockchain technology has found application so far in three main fields which represent the evolution of blockchain through time. It began with Blockchain 1.0 for cryptocurrencies, then to Blockchain 2.0 for smart contracts and other financial applications and more recently with Blockchain 3.0 for digital applications in the society.

In more detail, Blockchain 1.0 appeared first and is trying to be used as an alternative to the current banking system by adopting cryptocurrencies. The main benefits compared to the traditional system are its quick transactions directly between the participants of the network in a secure, traceable and anonymous way. The most famous cryptocurrencies are Bitcoin and Ethereum, however there are more than 1600 types which today reach a total market capitalization of more than 1.7 trillion USD (Coin Market Cap., 2021).

Blockchain 2.0 usage started for trading assets with smart contracts. Smart contracts are digital self executed contracts which don't involve third parties. The terms and obligations are predefined in a coded if/then logic and when a requirement is met then automatically the transaction is fulfilled. Since a smart contract exists only on a blockchain system it has many of its advantages like: avoidance of intermediate parties, reduction of paperwork, reduction on costs. Moreover, since the obligations of the contract are computer coded clauses there is no need for trust between the parties and a possibility of fraud is very small. Currently, smart contracts are already being used through different blockchains like Ethereum, Hyperledger and others, however they are mainly used in short term agreements with repetitive character. Long term and more complex contracts are not yet preferred to be done with smart contracts because it is likely that they would have to be subjected to modifications during this time which is not possible in a blockchain (Boucher et al, 2017).

Lastly, Blockchain 3.0 is extending beyond cryptocurrencies and financial transactions. It aims at keeping the main idea of blockchain technology and implementing it in a different spectrum outside of finance. Its main advantages such as decentralization, absence of third parties, secure network and transparency make blockchain suitable for being a database of keeping records of, for example, online voting, health care system, supply chain management, asset management and many more (Perera et al., 2020).

### 3.1.3 SENSORS - RADIO FREQUENCY IDENTIFICATION TECHNOLOGY (RFID)

During the last decade, the idea of internet of things (IoT) has emerged and has significantly contributed to the way antennas and sensors work by integrating them with radio frequency identification technology (RFID) (Rosenkranz et al., 2015). IoT can be described as a network of physical objects (things) which are equipped with embedded tags, sensors or similar technology and communicate, interact and exchange data wirelessly with other devices or systems via the internet (Rosenkranz et al., 2015; Li et al., 2014). Thus, IoT and RFID are two closely associated notions which have recently brought great innovation applications and they keep growing. According to Köhn (2018) IoT devices have been increasing by 31% each year for the last two years (Köhn, 2018).

Numerous applications have been invented for almost every industry. The most well-known are related to Smart Cities, Smart Farming, Military and Defense, Healthcare, Transportation, Logistics and Supply chains as well as Construction (Jia et al., 2012). More specifically, in AEC industry there have been applications for tracking materials throughout the supply chain, for monitoring working staff, ensuring safety, quality control, logistics, scheduling and many more (Costin et al., 2015). This research will address RFIDs' involvement in structural health monitor (SHM) and specifically on steel elements.

Despite the majority of studies being focused on RFID for aspects like the tracking of materials throughout the supply chain, there are also studies regarding SHM. Either in small scale experimented setups or in real case studies, it has been showed that RFID and IoT technology can be successfully applied in AEC for monitoring several characteristics of construction elements for both steel and concrete. From studies it was observed that almost every important characteristic regarding the behavior of a steel element in normal or severe external conditions (like earthquakes, extreme thermal changes etc.) could be measured with RFID tags. Occhiuzzi, Paggi and Marrocco (2011) studied how RFID passive tags can monitor the physical state of a steel element and more specifically characteristics of stress and strain, geometry and material alterations. Zhang, Tian & Zhao (2017) tried to find a non-destructive way of testing elements, hence with RFID they successfully measured the existence of defects and particularly of cracks as well as their length and behavior. A similar study was conducted by Mohammad and Huang (2010) were they explore how cracks occur and grow from fatigue while a study from Khalifeh et al. (2016) investigate corrosion of steel in coastal areas. Lastly, Kueng (2017) suggests RFID tags for measuring the temperature and humidity of different materials.

*RFID benefits over other sensor systems*

From a RFID technology review concerning structural engineering from Duan and Cao (2020) it was stated that RFID sensors prevail over other wireless technologies on the characteristic of battery. RFID sensors can be passive which means that there is no battery, while the required energy is received wirelessly from the reader. That also gives them the opportunity to be smaller, come at a lower price and last throughout the life cycle of the examined element since it does not require battery replacements. In contrast, what they lack compared with other technologies, which use sensors with batteries, is the long reading range, although they still have a decent reading range. Table 3.1 shows the different technologies with their respective transceiver type, frequency band range and reading range. Another element that shows the inclination of RFID technology for structural engineering is the number of published articles that surpass the publications of the other technologies (Figure 3.3).

Table 3.1. Characteristics comparison among the sensor technologies (Duan & Cao, 2020)

| *Technology* | *Transceiver type* | *Frequency band* | *Read range* |
|---|---|---|---|
| *RFID* | Passive or active | LF, HF, UHF, SHF | Up to 15 m |
| *Zigbee* | Active | 868 MHz. 915 MHz, 2.4 GHz | 10 – 100 m |
| *Bluetooth* | Active | 2.4 GHz | 10 – 100 m |
| *WLAN* | Active | 2.4 GHz, 5 GHz | 50 – 100 m |
| *UWB* | Active | 3.1 – 10.6 GHz | Up to 60 m |

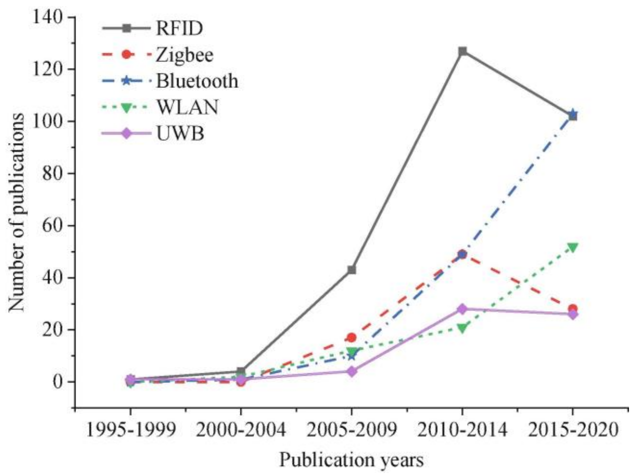


Figure 3.3. Number of publications for each of the different sensor technology (Duan & Cao, 2020)

<u>*RFID technology*</u>

RFID is a contactless way to receive data from a tag through a reader (Duan & Cao, 2020). A RFID configuration can be seen in Figure 3.4. It is comprised of four components the RFID tag, the RFID reader, the middleware and the database.

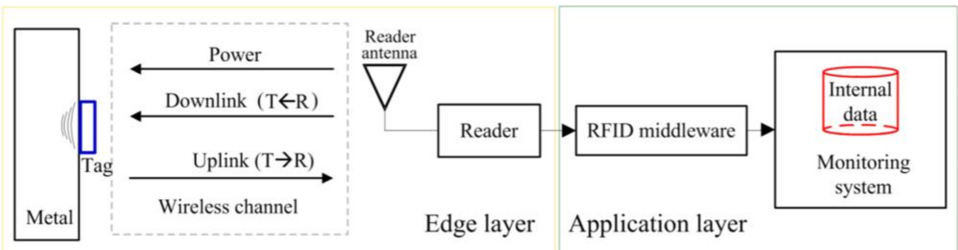


Figure 3.4. A typical RFID architecture (J. Zhang et al., 2017)

In more detail there are two RFID mechanisms, the near-field and the far-field. In a near-field system data and energy are transmitted to the sensor from the reader by inductive coupling. That is produced from changes of the magnetic field that is created among the coil antennas of the sensor and the reader (Figure 3.5). On the other hand, in a far-field system the two antennas are dipole and the communication is achieved with electromagnetic waves and backscattering (Figure 3.6). Hence the difference of the two systems lies on the frequencies used in each case, with near-field operating under low or high frequencies which leads to shorter reading distance, while the far-field system that operates under ultra high frequence can reach greater reading range. An estimation of the reading range of a passive sensor and a reader, according to the different frequencies, is seen in Table 3.2.

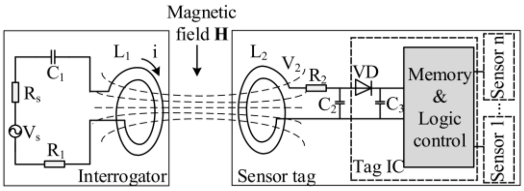


Figure 3.5. Near-field system (Cui et al., 2019)

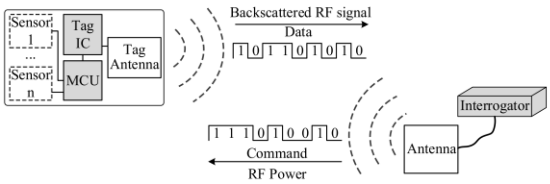


Figure 3.6. Far-field system (Cui et al., 2019)

Table 3.2. Reading range according to frequencies (Meng & Li, 2016)

| *RFID Frequencies* | *Operating frequency band* | *Read range* |
|---|---|---|
| *LF* | 125 – 134.3 kHz | Up to 10 cm |
| *HF* | 13.56 MHz | Up to 1 m |
| *UHF* | 860 – 960 MHz | 1 – 12 m |

*RFID components*

- *RFID sensor* (Figure 3.7) is attached or embedded in the objects of interest and it obtains the desired information from it. Sensors come in different shapes depending on the use they are intended to cover and the environment (Nainan et al., 2013). Usually, they consist of a chip, a capacitor, an integrated antenna and their dimensions are small - of the scale of $mm^2$ similar to the size of a credit card (ZHAW, 2017). The micro chip has a unique serial number and a memory which can be either read-only or read and write. The antenna transmits the data from the microchip to the reader. Antenna can vary in size, the larger the antenna the longer the range can be from the reader (El Khaddar et al., 2011; Zhang et al., 2017; Duan & Cao, 2020).

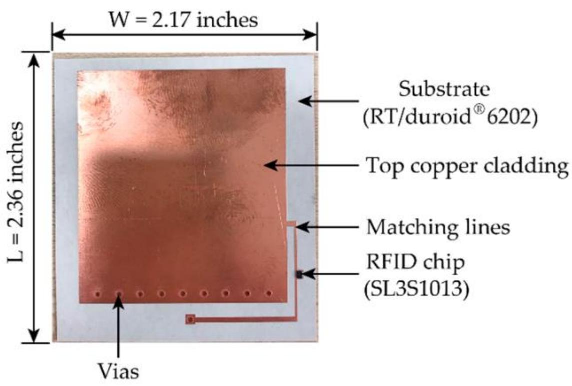

Figure 3.7. RFID sensor (Li & Wang, 2020)

As it was mentioned earlier during the comparison of rfid with other technologies, there are two main types of sensors. Those who are powered from a battery are called active sensors and those that do not have a battery and are powered from electro-magnetic waves from the reader are called passive sensors (El Khaddar et al., 2011; Duan & Cao, 2020). However, there is also a third type, a hybrid passive-active sensor which has a dual operation mode. That can be in principal a passive sensor with an addition battery and an energy harvesting chip. The energy can be harvested from different sources such as solar energy, heat energy, etc., upgrading it that way to an active sensor. An example of a hybrid sensor is shown in Figure 3.8.

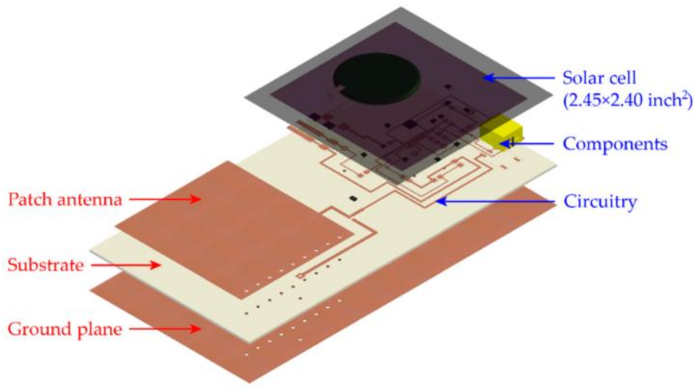

Figure 3.8. Hybrid passive/active sensor (Li & Wang, 2020)

*How they sense*

For every different characteristic that is aimed to be measured a different sensor is used which involves a different sensing technique. The most common and important characteristics for structural steel elements are the strain measurement, crack, fault and corrosion detection. Table 3.3 summarizes the sensing technique from some of those characteristics. Furthermore, Appendix A presents three different case studies explaining in short what sensor have been selected and how the desired characteristic had been measured. For most of the characteristics mentioned above when the selected sensor detects even a slightest change then this is translated into a shift of resonance frequence while it is transmitted back to the reader. From this variation of the resonance frequence the intented characteristic can be then measured. Figure 3.10 is an attempt to depict this frequence variation when a crack starts to form.

Table 3.3. Sensing technique and frequency band example for measuring different characteristics (Cui et al., 2019)

| *Measured characteristic* | *Frequency band* | *Sensing Technique* |
|---|---|---|
| *Strain* | UHF | Resistive strain gauge |
| *Metal crack detection* | Chipless sensor - UWB | Microstrip patch antenna resonator |
| *Fault diagnosis* | UHF | Accelerometer |
| *Displacement* | UHF | Deformation sensor |

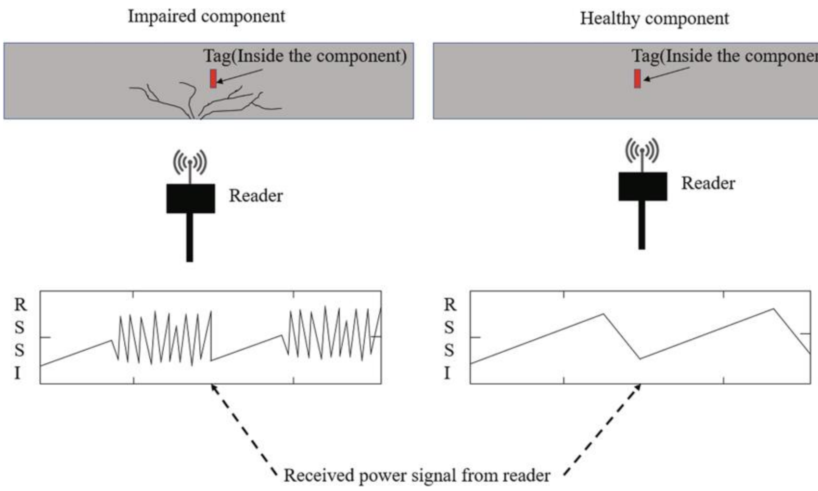

Figure 3.10. Frequency variation indicating crack (Duan & Cao, 2020)

- *RFID readers* are devices which communicate with the sensors, receive data and then pass them to the middleware wirelessly. Readers have their own antenna which can communicate with the sensors of their range as well as supply them with power in case of passive tags. They can also process data from multiple tags simultaneously without the need of being in line of sight in and even in harsh environments (Nainan et al., 2013).

- *RFID middleware* is a software or a device that receives and manages the data coming from the reader and process them. Middleware tries to filter and format the raw data received from the reader in order to make them usable. More specifically, it has to handle the flow of a huge amount of real-time data coming from multiple readers at the same. Then the processed data are forward to the backend database (El Khaddar et al., 2011; Nainan et al., 2013).

- *RFID backend database* is where all the data, recorded by the tag and communicated by the reader and the middleware, will be stored. A benefit emerging from IoT is that data can be stored in a cloud database (Chen et al., 2014) or in blockchain database (Copeland & Bilec, 2020).

## 3.2 CURRENT SITUATION - PROCESS ANALYSES & ACTORS

Reuse strategy, apart from the significant environmental benefits over recycling and the ease of deconstruction, sometimes also triggers the element of competitiveness among companies. In our case, a client of such a project can be either from the private or the public sector. A growing number of companies have started to integrate circularity aspects in their projects. Apart from the inherent vision of a company to integrate circularity, it can also be used for increasing reputation and creating a sustainable profile in order to attract more clients. Especially in the public sector, national, regional or local governmental bodies very often conduct tenders for projects that require a certain level of circularity as well as they fund or give incentives to environmentally sustainable projects. Those levels can be measured by several assessment tools in each country. For instance, the Netherlands and U.K. use the Building Research Establishment Environmental Assessment Method (BREEAM) while the U.S. uses Leadership in Energy and Environmental Design (LEED). Consequently, applying a reuse strategy will award some credits, this may be determined depending on the level of reuse, if for example are reusing only parts of a structure such as primary or secondary structure or a facade. Indeed, it is likely in the near future, that Europe develops a common certification system in order to promote sustainability even more (European Commission, 2011). There is already, an extra pressure at a European Union level to the construction industry to become more environmentally friendly i.e. to reduce waste, to reduce embodied carbon emissions and overall adopt circular economy strategies.

A typical steel reuse procedure starts with the client who desires to build with reused steel informing the design team in the early phases of the project about that decision. The structural designer has to list all the required sections along with their properties (dimensions & strength) as well as prepare a few alternatives. This information has to pass down to the structural engineer (the contractor who is responsible for the construction of the steel structure) in order to start searching for available reusable sections. The structural engineer will look in other construction sites, demolition sites, stockist and salvage yards to find steel sections. It is also his responsibility to visit those sites, to inspect and, in communication with a fabricator, check their condition. The fabricator is a steel expert who will examine and judge if the sections are capable of being reused. Some of the examined properties of a section are the size of its cross-section, its straightness, bow and twist as well as its finishing, i.e. if it is galvanized or has a special painted finish. Moreover, sections are checked for possible characteristics that indicate their manufacture date. Also, attention is paid to plates, bolts and bolt-holes that may be fixed to the beams and potentially be taken into consideration. Finally, in case there is still uncertainty regarding the steel section's stress it is necessary to take a sample for testing to verify its limits.

When the inspection is over and an overview of the selected steel sections is made then the structural engineer in consultation with the structural designer will agree whether they are satisfied with the products or not. If the quantity and quality of the reused steel sections is not sufficient for the project then new steel sections will be purchased to supplement it. Assuming that the required steel has been found, some further adjustments to the length and the coating (painting or galvanizing) are made wherever that is needed. The final step would be their transportation to the construction site and there the tasks continue as they would have with new steel.

According to the literature (Densley Tingley et al., 2017; Drewniok et al., 2017) there are three types of sources in which reused steel can be harvested. The more generic source is from stockholders, salvage yards or buildings which have reached their end-of-life and in some cases, they are even abandoned. There are many steel-framed buildings which are reaching their end-of-life and they could be a good source for a new project but due to lack of vital information regarding their steel condition it is happening in limited cases. One of those cases was the research of Pongiglione & Calderini (2014) where they designed the new train station of Genoa using steel from an old industrial complex located in the suburbs of the city. The old industrial complex was satisfying all the requirements, it was relatively close to the train station and it could offer large amounts of steel.

Another important aspect of this generic source category is that there are many different actors with similar scope of work and in some cases, it is confusing which one to involve. There is the fabricator, the material dealers, the service centers and the salvage yards. Often their role is overlapping and usually not all them are needed. Which of them are necessary depends each time on the project characteristics' and the location.

A brief analysis of the above actors follows in order to make their differences more clear. Service centers or stockists refer to businesses which stock steel products, do a basic first stage processing of the steel as well as its distribution. They also act as intermediaries among the end user and the fabricator. Similar to the service centers are the salvage yards where they acquire and store building elements which are already ready for reuse. They do not get involved with repairs or modifications. Material dealers are also doing a relevant job as the service center and salvage yards however they do not possess a storage place, they act as mediators directly on demolition sites and they try to sell the reclaimed materials directly from there. The materials that are not sold for reuse purposes, are sold for recycling. Fabricators are the steel experts; they are hired to inspect the steel elements of the service centers, salvage yards or the material dealers and if necessary they will carry out all the appropriate refurbishment according to the needs of the project. Some fabricators may also own a storage yard with a stock of reclaimed steel from the dismantling of old structures. Lastly, they will often take over the erection of the structure with their own crew or they will employ a subcontractor.

There are also two other less frequently observed source cases in which an existing structure is relocated or rebuilt in the same location (in-situ). In both those cases it is common that the existing steel frame can be reused, that is something that will limit the need for new steel sections.

More specifically, there might occur different reasons for relocating a structure. It can be either forced, due to, for example, government infrastructure plans or due to other business strategic plans of the owner which will lead to such a decision. In relocation, the structure will be deconstructed and its main structural elements will be transferred to the new location where they will be used to erect it again. An example is the SEGRO warehouse in Slough, U.K.. The original building was located, for 15 years, at where eventually a new road bridge would be constructed to accommodate the western train line from London. The whole relocation from the dismantling to the rebuilding phase lasted 56 weeks.

While in the in-situ case, the building will not be removed from the site, but it could have major alterations like changing its purpose and get rebuilt or renovated. An example is the power plant of RWTH Aachen University where it was initially used to provide heat. After some years it was shut down and currently it has been renovated to a seminar building.

## 3.3 PROBLEM STATEMENT

From the above described procedure, this research will focus on the course of steel elements through the phases of a project and how information is safeguarded, instead of getting lost, through those phases and through time. The ultimate goal is to have sufficient information at the end of a building's life about the steel elements in order to make reuse more accessible than it currently is. In this section several issues which restrain steel reuse will be analyzed.

For decades now, AEC projects have been based on 2D CAD drawings. 2D CAD drawings represent the old traditional analogue representation type which with computerization became much easier to execute, to make alterations and to share among the involved actors. Even so, they remain a depiction of a three dimensional structure constrained in a two dimensional drawing (Koutamanis, 2019). Moreover, a switch to different way of operating (i.e. BIM) is not that easy since the vast majority of engineers are experienced in working with traditional CAD drawings and at the same time small and medium size projects, which employ most of the engineers, have lower cost when conducted with CAD (Czmoch & Pękala, 2014).

One of the main differences between the two design options lies in the idea behind the style of drawing. 2D CAD is based on analogue representation of models with, basically, drawing lines and poly-lines to create the desired geometry of each single object of the drawing. For example, a wall, a beam or a door are not inserted as a whole object but they have to be drawn with individual lines or rectangles and then get trimmed in the meeting points. With that method, objects are illustrated as pictorial representation and not as symbols. Sometimes this can constitute a problem considering they heavily rely on the perception of the people who will read them. Meaning that if a 2D drawing is not fully detailed there may be misinterpretations. Furthermore, the pictorial representation of the geometry of the objects, apart from the dimensions (length, width) of the lines which represent an object, lacks any other information such as material properties, type etc.

It is understood that with this method the reuse of steel elements, cannot reach its full potential. Until recently it was calculated that only around 6% of steel structures are being reused (Densley Tingley & Allwood, 2014) and one of the reasons for that is the limitations of 2D CAD. From the above mentioned, it is clear that having only 2D drawing for the design phase of a project is not enough. Not only that, but also the absence of critical information regarding the steel elements at the design, construction and operation phase.

By not adopting a way of working which includes important attributes throughout a project lifecycle vital information regarding reuse will not be incorporated. For example, such information concerns the damage that they have received through the years, their assembly sequence, their maintenance, their repairs, potential replacements as well as their exposure to weather conditions or other external loads. The majority of ordinary buildings that have been built more than 10 years ago, when they reach their end-of-life, they lack that information simply because they were based on CAD. CAD models even if they are 3D do not contain any structural details nor have the connectivity with other softwares, e.g. external databases (Eastman et al., 2011). Moreover, CAD models are created in the very early phase of the design and since then they undergo many changes until they reach the final product. For example, it is likely that structural engineers execute iterations with different elements to address inconsistencies during the construction which will lead to a different design from the original. But even if no changes occur, without a transparent and secure database with access from all the involved actors for the whole duration of the project, those designs will probably stay only in the designing company servers and they will not get further exploited.

One direct outcome of the insufficient gathered information is that in most cases if a steel element is to be reused it has to go through evaluation. The evaluation will require new actors to get involved and execute (destructive or non-destructive) tests to the steel elements to check their condition. Ensured quality along with certification is very important aspects that steel elements should possess before reusing. This is very crucial because apart from the safety side which is the most important to be assured, it also addresses some traditional beliefs that the old is of inferior quality compared to the new. Eventually that is translated into a problem for the client since by increasing the tasks and the actors it is likely that budget and time delays will also increase. Furthermore, another collateral problem of inadequate information is that due to the lack of traceability and historic data of the steel elements and due to the overlapping mentioned roles of certain actors it is possible that liability, trust and insurance issues might occur among the different actors.

# CHAPTER 4 – FRAMEWORK DEVELOPMENT

*This chapter is divided in two main sections and at the end its summary. Each section refers to a phase of the lifecycle of a steel element. Subchapter one focuses on the design and construction phase where BIM can make an impact. The capabilities of BIM regarding the case of reuse are mentioned and what information should be included on a BIM software during this phase. The next section refers to the operating and maintenance phase where the potential added value of RFID and blockchain technology are examined. First, the appropriate characteristics of such a system are presented and then an integration with a blockchain database is displayed. In order to explain better the potential blockchain platform, its architecture as well as some technical characteristics are explained. Finally, the last section is the summary where an overview of the above described sections is explained schematically through a diagram.*

## 4.1 DESIGN & CONSTRUCTION PHASE

BIM has been growing and has come to cover some of the gaps that 2D CAD method leaves. BIM uses a different approach in designing, instead of drawing objects with lines and polylines it inserts symbols. So, at the end, the model will be a set of symbols instead of a set of just lines. A symbol represents an element or a space. Usually software contains a predefined set of symbols however it is also possible to create new ones or insert other types from different libraries or even insert directly from a specific manufacturer. The most important characteristic though is not only the ease of designing with symbols rather than with lines, but that the symbols can also contain information about the element that they represent (Figure 4.1). Apart from the information that can be deducted from the graphical representation of the 3D model, any other information like material properties, structural capacities, type of the element, position, dimensions etc can be inserted in the symbols. In the same manner as with the elements, spaces can have attached information too. Such information might be related to the kind of use of the specific space or what activities will take place there etc. This kind of data will help extract information for elements that have the potential to be reused. Like for example, if a space is intended for the storage of paper - a material which in large quantities constitutes a significant amount of weight - then the supporting beams of the room will probably have to be checked (among others) for bending.

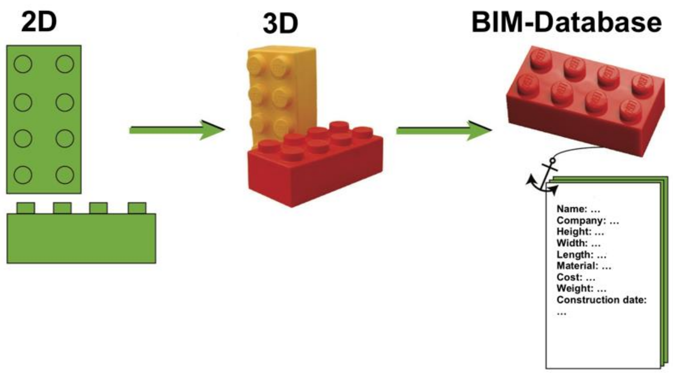


Figure 4.1. Lego example of visually evolving from 2D to a BIM Database (THM, 2016)

In this study the focus will be on steel element symbols such as columns and beams. Having a proper design and a database in BIM with all relevant information regarding the steel frame of a building is a good starting point for gathering data at the first phase of a project. It is important to have recent updated designs of a building, since from the design phase until the building is constructed and delivered many alterations might occur. In a BIM model those alterations can be an easy and fast task to do in contrast to 2D CAD.

Another essential ability of BIM that can enhance the reuse process lies in its interoperability. As explained in chapter 1, IFC promotes connectivity among different software, each for different purposes. For instance, the structural engineering model can be combined with the architecture model and the MEP (Mechanical, Engineering & Plumbing) model providing a complete overview of the building. By having everything together it is easier to detect the relations among the elements and among elements and other components, like for example the contact of a column with a water network system.

Bellow all the required characteristics of the element, which will enhance reuse by recording them in a BIM model, will be analyzed.

- <u>Material Properties</u>. In this category the most important characteristic is the steel grade, i.e. S235, S275, S355 etc. From that, other properties like thermal expansion, elastic modulus E, density etc can be deducted. In most BIM software the steel grade category already exists in their element's libraries, so it just has to be assigned to it.

- <u>Types of steel elements, cross-section and section properties</u>. This characteristic apart from its visualization on the model has to be inserted when defining the element. Steel elements are distinguished by the different standardized cross-section profiles that they have. For instance, beams can have an I-type profile, an H-type profile as well as many other profiles. Similar goes for columns. Apart from the standardized cross-section profiles, it is common to create customized steel elements. By welding, usually, beams to other steel parts (in general with pieces from another beam) a new unique cross-section profile is created. Both cases are vital and have to be included in the BIM model. BIM software contains in steel elements options the main standardized cross-section profiles however the customized ones, have to be defined. Cross-sections except from the type of the steel element, include information for the dimension and other valuable section properties.

- Elements Capacity and Loads. Knowing the maximum capacity (moment and shear capacity) of each element along with the loads they bear is useful in determining the overall damage by the building's end-of-life. If for example they are loaded near their capacity limits, through-out the building's life cycle, they may present bending problems. Structural software can be used for the structural analysis and then communicate the results in the model.

- Elements connections. BIM provides the possibility to describe and display the relation between elements. More specifically, information about the connection of elements, like "beam to beam" or "column to beam", which at the deconstruction phase will be useful for assessing them. In reusing strategies, a connection with bolts is preferred over a welded connection. In the second case the element will have to be cut and therefore lose part of its length as well as cost more in terms of money but also energy.

- Assembly information. For the deconstruction phase it is important to know the sequence that the elements were assembled as well as their weights, to make the disassembly procedure easier. Moreover, other kinds of information can be added here like lifting requirements.

- Location information. The attribute of location of the building should also be registered in the elements. It would be useful for future decisions regarding the dismantling elements and the selection of the closest fabricator, storage place or recycle center. Based on this, the distance of the structure from the potential facility can be measured and help in the decision taking into consideration transportation costs as well as environmental burden of each choice.

## 4.2 OPERATION & MAINTENANCE PHASE

### 4.2.1 SENSORS

#### 4.2.1.1 IOT & RFID

Having collected and registered in BIM all the necessary information of the early phases of a project; an important first step has been achieved. To go further than that IoT and RFID integration in AEC projects can increase the digitalization of the industry even more and substantially contribute to many different applications. In our case that is by monitoring desired attributes of building elements during the Operation and Maintenance (O&P) phase of the structure.

Operation and maintenance phase is an ongoing process which lasts throughout asset's life cycle and demands constant updates of the structure condition. A structure which is exposed for decades to operational and environmental loads is inevitably going to present signs of deterioration like fatigue or corrosion (Zhang et al., 2017). Currently in order to monitor a building element, a worker is assigned to manually apply inspections and tests where deemed necessary. This process relies on the experience and the efficiency of the working crew which in many cases is time and cost consuming (Costin & Teizer, 2015; Akcamente et. al. 2010). RFID combined with IoT can automatize this process by replacing the manual inspections with recording real-time data and promoting preventive maintenance leading also to more cost-effective solutions (Costin & Teizer, 2015). Moreover, as it was explained in Chapter 3, RFID sensors have the capability to measure many different attributes. A synopsis can be seen in Table 4.1.

Table 4.1. Synopsis of values which can be measured with RFID technology

| MEASURED VALUES |
|---|
| CRACKS |
| DEFORMATION |
| STRAIN |
| CORROSION |

#### 4.2.1.2 RFID SENSORS IN BIM

RIFD sensors and readers can also be imported as a separate symbol in BIM (Motamedi et al., 2016). They can be either customized designed by "family" option in a BIM software or they can be downloaded, if available in BIM form, by the company which provide them. In Figure 4.2 there is an example of creating a symbol for a tag in Revit. The symbol representing the tag is fully customizable and can contain attributes like its geometrical information, its unique ID, the ID of the element which is attached, its type, its material, the frequency band as well as information regarding which characteristic is measuring. Furthermore, another positive aspect of importing tags to BIM and assign them to steel elements is the visualization of the system element-RFID as well as their location. In Figure 4.3 a draft outline of an RFID tag attached to a beam is drawn in Revit.

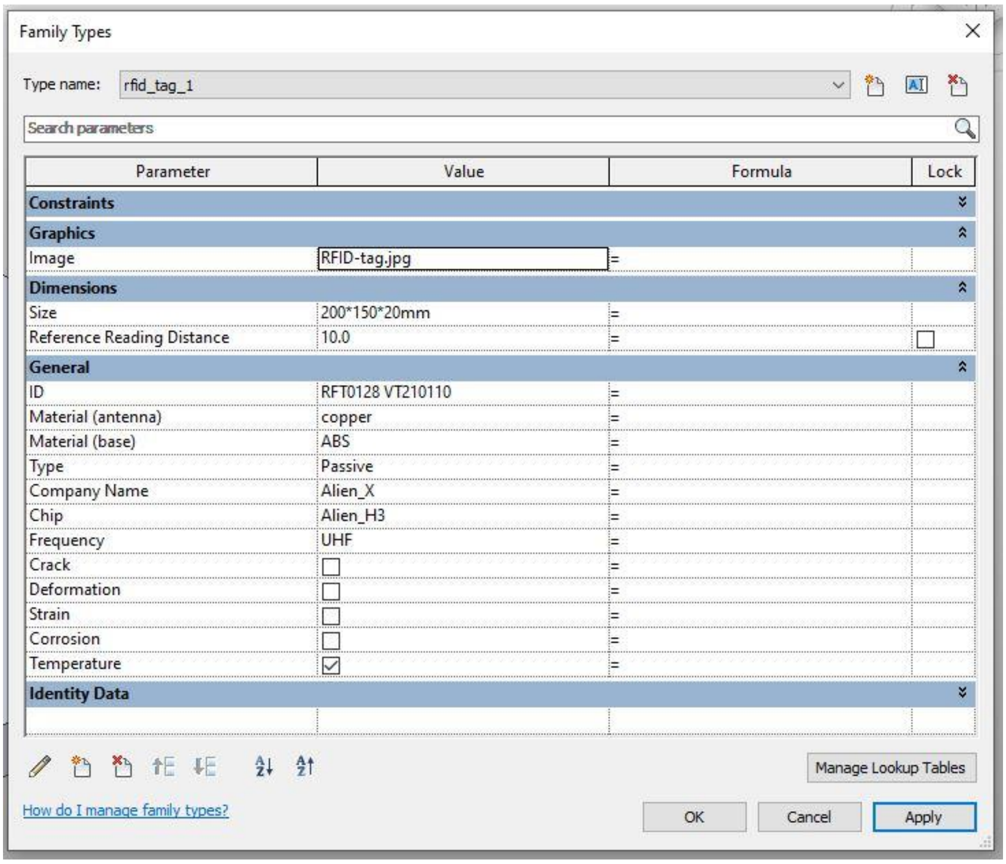


Figure 4.2. A RFID tag and its properties as it was inserted as a building element in Revit

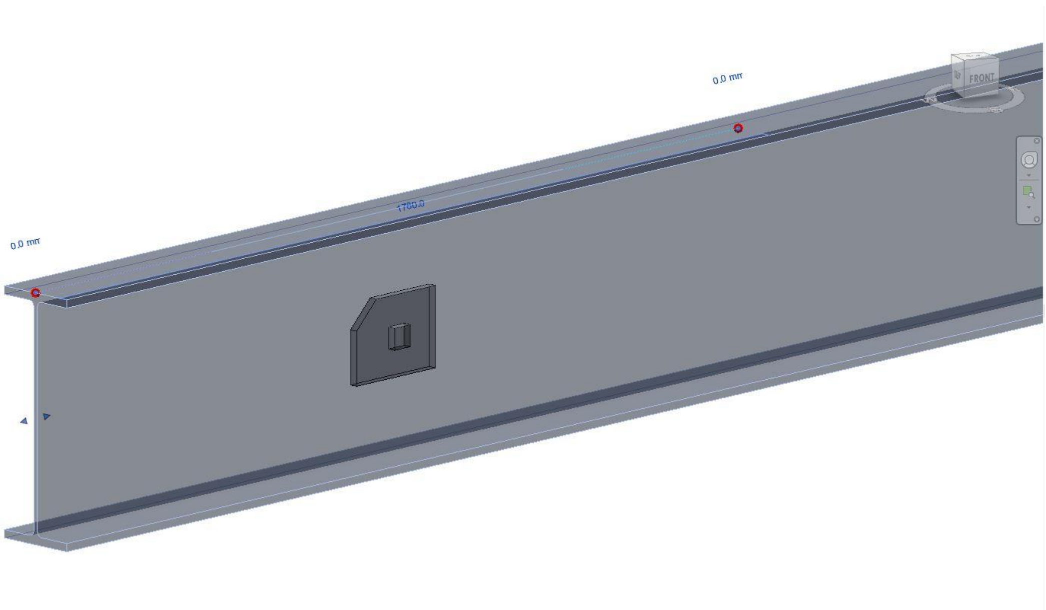

Figure 4.3. An RFID tag attached in a beam, drawn in Revit

### 4.2.1.3 Choice of sensors and used Frequency

Having described in detail how RFID sensors work in section 3.1.3, this section would provide further clarification on what aspects should be taking into consideration for this particular study.

As it was stated in section 3.1.3 the reason for selecting RFID sensors was based on its passive and wireless characteristics. However, to fully exploit those advantages, sensors have to be under readers proximity. An ideal set-up would be that each sensor has its own reader. However, it has to be considered the fact that now there are companies which produce readers that can reach up to 15 m reading range and at the same time communicate with all sensors in their proximity. Thus depending each time the architecture of the structure it can be suggested a scheme with multiple nearby sensor "answer" to one reader. In case less readers are desired then the data from sensors, which are out of range, have to be collected manually. Sensors chip have the memory to store data for a few days, so that means that someone or "something" has to pass near them in order to connect with them and collect the measurements. In extension to that and in order to avoid having someone that's collecting everyday data an unmanned approach could be selected.

Another sensor parameter is the frequency band which though it communicates with the reader. In almost all AEC related case studies UHF prevailed over the other frequency bands due to the long reading distances they offer. Only in one of them High frequency was preferred due to some topology and material restrictions. So, overall a passive tag operating in UHF range is the optimal solution for adopting in typical steel structures with its attachment happening either in the fabrication phase or directly in the construction site and accompany the elements throughout their lifecycle (Costin & Teizer, 2015).

Finally, depending on which characteristics regarding the state of an element the focus is on; a different approach can be selected for its inspection. For example, there can be a constant flow of measurement (real-time data input) of a specific characteristic (e.g. a crack) or it can receive data with a certain frequency e.g. every 5 hours, 5 days etc. or it can receive data manually when by opening and closing the system after a certain incident occurs. In our case, it is suggested to continuously measure but record under the approach proposed in section 4.2.2.1.

### 4.2.2 BLOCKCHAIN

With the invention of wireless sensors and later on the evolvement of IoT and its integration to SHM; significant benefits have arisen. Sensors attached to elements can provide more reliable real-time data, which in the long term, are more cost effective than traditional SHM practices (Jo et al., 2018). It has become obvious that these technologies require the existence of a database to store their data. Currently, IoT systems use centralized databases which cannot cope efficiently enough with the immense amount of connected devices and data that need to be managed. Consequently, several drawbacks have appeared regarding scalability, data security, transparency and safe transactions among the involved participants, single point of failure as well as bottlenecks to the network (Jo et al., 2018).

At the same time, the emergence of blockchain has started to attract interest and can be employed in applications outside of cryptocurrencies. Its decentralized nature, the lack of third-party involvement as well as its intermediary fee expenses, and the immutable and secure nature that it offers make it ideal for a database solution in many different fields. There have been already cases where blockchain has replaced traditional databases while researchers state it has the potential to grow even more and in combination with IoT add value, among others, in SHM (Reyna et al., 2018).

In order to consider applying a blockchain database, several studies propose decision trees to assess whether a blockchain or a traditional centralized database is preferred. Certain critical questions are being answered, depending the use case of the database, based on which someone can conclude which one to adopt. For example, Suichies (2015) and Chowdhury et al. (2018) suggest a decision tree which leads to either no-blockchain or to public, private or hybrid blockchain. Similarly, Seuren's (2018) decision tree also points out one of them, and furthermore highlights the reduction of transaction costs when applying blockchain database. The decision trees can be found in Appendix B.

So far, in SHM many different untrusted actors are involved and exchange information among each other. That information usually is confidential and companies as well as clients don't want to fell in competitor's possession. SHM data are targeted and they are easy to access and tamper by competitors which aim to make profit from that. This rises awareness to the type of database that is used, the security of its content and the involved parties.

Taking into consideration the above articles, a *private permissioned blockchain database* can be employed for the purpose of this study. Predetermined nodes will have access to it while only those that are authorized can write data. For instance, this can be a monitor team, a contractor responsible for maintenance and replacements, managers and the client.

It has to be mentioned that a traditional database could be also applied and meet the requirements of this study, however by selecting a blockchain system aspects of security, transparency, immutability and trustiness are emphasized. Moreover, Christidis and Devetsikiotis (2016) and Botta et al. (2016) imply that integration of blockchain with an IoT system has reduced maintenance costs compared to a centralized database solution.

#### 4.2.2.1 Architecture of the system

Blockchain works as a transaction recorder, however in case additional information is desired to be included then they are stored off-chain in a separate third-party cloud system. In the present study, it will be only used as a transactional recorder and more precisely an event recorder. The next paragraph describes what will be the event.

RFID sensors are attached to the desired elements and transmit the data that are set to monitor. RFID readers receive the data from the sensors and send them to the middleware. Middleware works as a "bridge" between the two technologies, the RFID and the blockchain database. It receives the raw data from the readers and as a first step it filters them, preprocess them and structures them, if needed, then as a second step, it compares them with critical limit values that are defined by the user for each aspect that is monitored (i.e. strain, corrosion, deformation etc.). When the recorded data values surpass the critical values then this event is inserted as an input transaction in the blockchain. Once it enters the blockchain, a block is created that is timestamped and carries the id of the element as well as the type of value that was monitored. Once the block is created then is added to the chain and cannot be deleted or altered by anyone. That way, the immutable nature of the information is safeguarded.

It is important to highlight that since the measures are based to RFID technology it is rational that some of the occurred events might be faulty, hence to be on the safer side it would be wise to also register to the ledger some of the previous and some of the after measurements of the event in order to identify if it was a fault detection.

Depending on how critical values have been set, different stages of an element's deterioration can be monitored. For instance, if a displacement of a beam is being monitored, it is crucial to set more than one critical value to have a better insight of the behavior of the element. So, in this instance, the critical values can be set to: (i) detect a small-scale displacement, (ii) detect near failure value or (iii) another characteristic limit-value in between of those. Consequently, in case of surpassing the small-scale displacement, this creates an event send to the monitor team that interprets it as a problem that might occur in the future and the continuation of monitoring is needed to follow its progress. While if a failure critical value is surpassed then a replacement is required. By doing that and breaking down the inspection level of deterioration into more critical values, a more complete and more detailed image of the history of each element can be obtained.

One method to visually describe a system's architecture is with the Unified Modeling Language (UML). UML offers tools to describe software-based systems, database systems, models and in general different kinds of processes (Object Management Group, 2011). Depending on the type of content that is to be described, there are several types of UML that can be used to described it better. In our case, the Sequence Diagram will be deployed. Sequence diagrams depict the content that is to be described as objects that interact with each other in a sequence order (Bell, 2004).

The proposed Sequence Diagram is presented in Figure 4.4. For more clarity, RFID sensors and RFID reader are grouped and displayed as a one object named "sensors". Middleware is split in two objects to distinguish the two different process stages that data will undergo, the one of filtering/structuring and the other of comparing them with the critical values. Blockchain database will be the third object while the last object will be the accessing of the information and the decision on whether a maintenance or a replacement is needed.

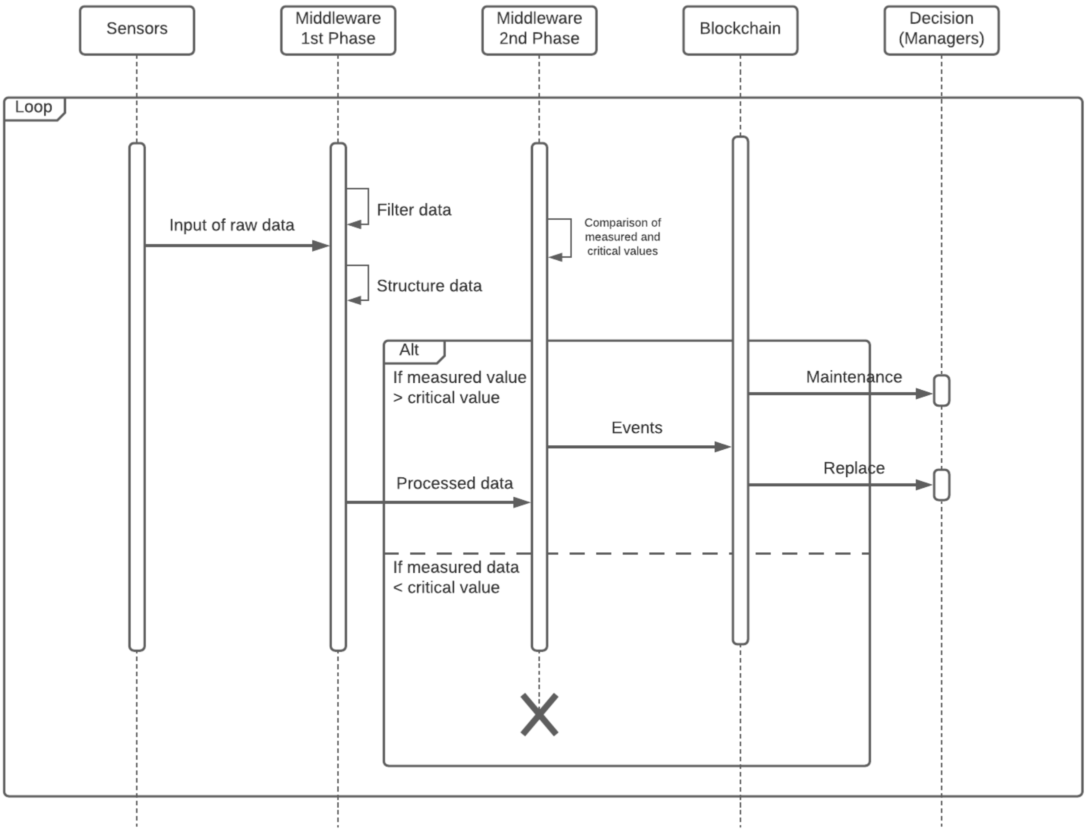


Figure 4.4. Sequence Diagram of the process

#### 4.2.2.2 Technical Characteristics of the Blockchain Database

This section describes some technical characteristics of the intended blockchain database. The scope of the study does not include in depth technical analyses, however for completeness purposes a few of the most important technical characteristics will be defined and explained.

According to Tasca and Tessone (2019) a blockchain distributed database can be described by a taxonomy of components that are related to each other in a hierarchical way. Each main component is composed of subcomponents and if necessary from sub-subcomponents. Some of the main components are: (i) Consensus, (ii) Identity Management, (iii) Transaction Capabilities and (iv) Extensibility.

i. Consensus. The first main component is consensus which is responsible for the set of rules that govern the ledger and for the mechanism that the transactions are recorded to the ledger with a secure and immutable way. One of the subcomponents is the mechanism of validating the transaction, which was also explained in Chapter 3, and it can be one of the following: Proof-of-Work, Proof-of-Stake, Proof-of-Authority and many more. In a case like the one that is proposed in this study the most suitable is the *Proof-of-Authority*. Proof-Of-Authority is mostly used in private consortium blockchains and it gives the authority to some pre-selected nodes to do the mining. They can verify new blocks while they can decide who has only read or read and write option.

Another subcomponent that should be defined is the *gossiping* which is the way that information is exchanged across the network of the participants. In private consortium blockchains that is selected to *locally*.

ii. Identity Management. Here the type of blockchain is defined. According to the sensibility and the use of exchanged data it can be decided who joins the network, who has read and who has read and write option. Hence the choice of: Public, Permissioned Public or Permissioned Private blockchain is made. As it was noted earlier the ideal type for the purpose of this application is a *Permissioned Private blockchain*.

iii. Transaction Capabilities. This component expresses the scalability of a blockchain application. In our database, one of its subcomponents is the "*transaction model"* which describes how the ledger works and for private blockchains is selected to be *"traditional ledger"*. A second subcomponent is the accessibility of the nodes in different layers of information on the network. In our case this is defined by "Thin Nodes Capability" where not all the nodes have the same level of access in the network, "thin" nodes have less than others.

iv. Extensibility. This component describes the level of integration with other related technologies as well as its interoperability and its intraoperability. Here one of the subcomponents is that one of *governance* which is set as "*technical"*. Private blockchains are usually of a smaller scale than public ones and often are patented in order to meet the specific needs of the business that adopt it. Hence, a technical governance allows other experienced companies (IBM for example) to act as consultants.

#### 4.2.2.3 Blockchain Platforms

The most well know blockchains are the Bitcoin and Ethereum, however Bitcoin is only related with cryptocurrencies and Ethereum is offered only for public permissionless applications. The last few years more and more blockchain platforms occur that are don't necessarily aim for cryptocurrency applications but provide other business-based applications. One of the popular blockchains for businesses is the Hyperledger. It was the first to host private permissioned solutions for businesses and the second (along with Ethereum) that introduced the concept of smart contracts (Iredale, 2020).

Hyperledger is an open source platform that hosts enterprise solutions for applications in different fields like IoT, supply chain, finance and other. Hyperledger has under its umbrella different sub-platform; each for different use. The one called Hyperledger Fabric contains all the above-mentioned technical characteristics and components to potentially facilitate our case. For an easier application and to avoid "building" a blockchain from open source, Hyperledger Fabric collaborates with IBM. They provide tools and support to customize a blockchain platform for businesses simpler. There are also other platforms that facilitate such a case, for example Corda or Ardor.

## 4.3 OVERVIEW

Overall, each phase of the life cycle of a steel element was studied independently and it was attempted to assign digital technologies. By recording the proposed information, of the described steps, then each element may possess all the required knowledge in order reuse strategy to be enhanced. If that is to be achieved then structures can be considered as material banks, while intermediaries and fabricators might not be required any more.

Figure 4.5 (framework) summarizes schematically what was described in the previous chapters. It is an overview of each phase of a steel element and what information and in what way needs to be recorded for achieving improved reuse results.

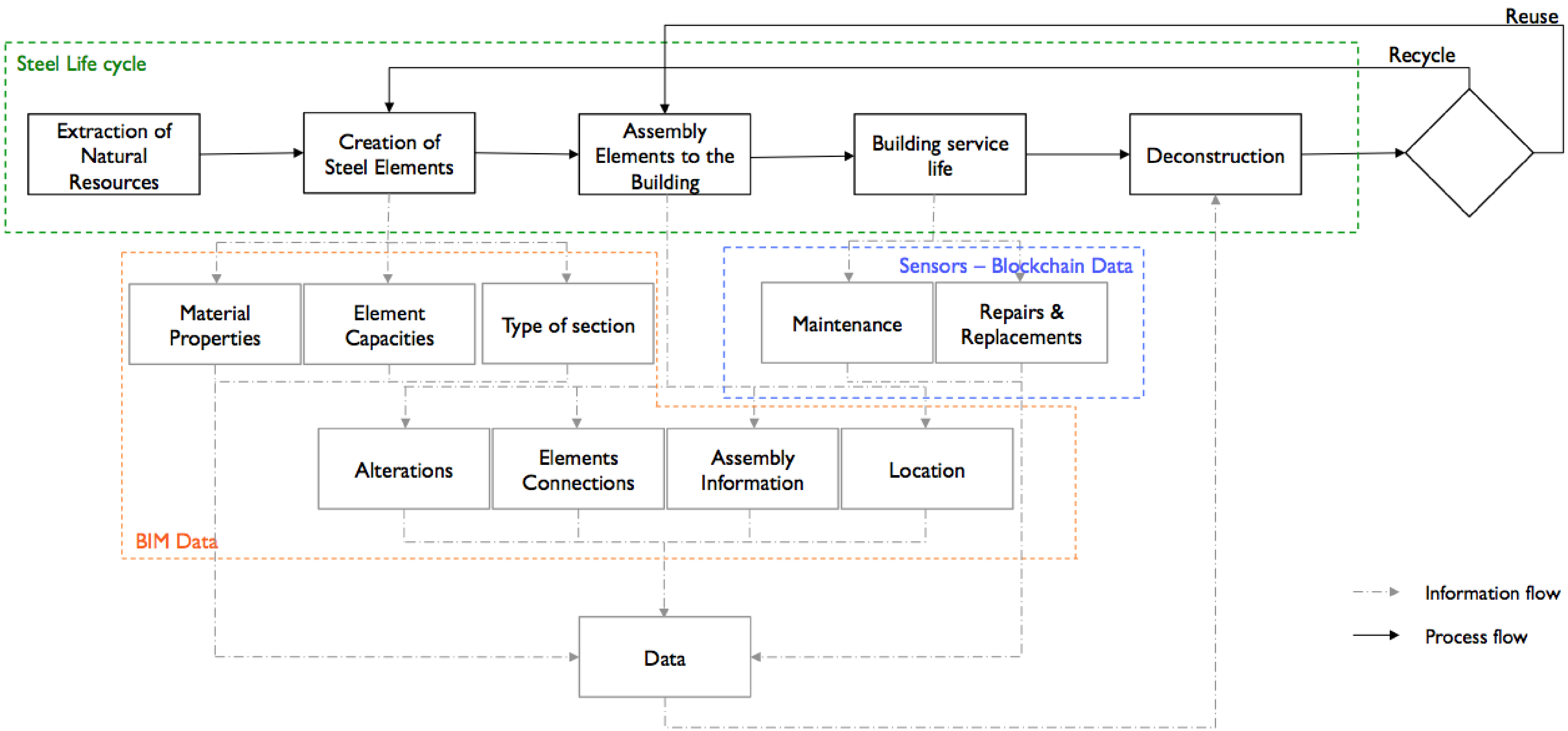


Figure 4.5. Framework

## 4.4 DEMONSTRATION

In this section an example will be given in order to make the framework more comprehensible. For this reason, a steel beam's information would be registered during its design, construction, operational and maintenance phase.

Starting from the design phase, the designing team starts the modeling by using a BIM software. Architect and structural engineer during that phase would have to, apart from the design and analyses of the structure, insert the suggested information of section 4.1. For the example of a steal beam, if supposingly there it is a steel beam with a profile type of IPE then profile dimensions for the specific profile should be inserted accompanied by its steel and cross-section class. In Figure's 4.6 yellow box it can be summarized what information would occur during this phase.

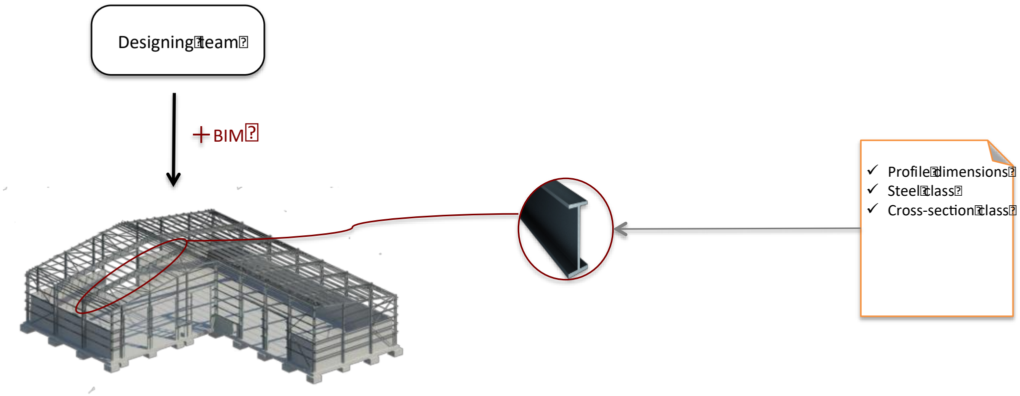


Figure 4.6. Illustration of the information registered during the design phase

Moving on to the construction phase, here the project managers have to inform about any changes that might occur during the construction and deviate from the initial design as well as about assembly details. For example the sequence and the relation of the installed steel elements in relation with other elements of the structure such as mechanical, electrological or plumbing elements. That would create a more realistic view of the structure which would be useful during the deconstruction phase.

During the O&M phase sensor selected to monitor specific characteristics would constantly monitor and record only when disturbancies (or events) according to the method described in 4.2.2.1. A monitoring team would supervise the measurements and the registration to the blockchain database. Figure 4.7 illustrates the steps and the potential information that could be registered. Eventually at the end of life of the building steel elements would have sufficient information in order for a decision towards reuse to be more viable (Figure 4.8).

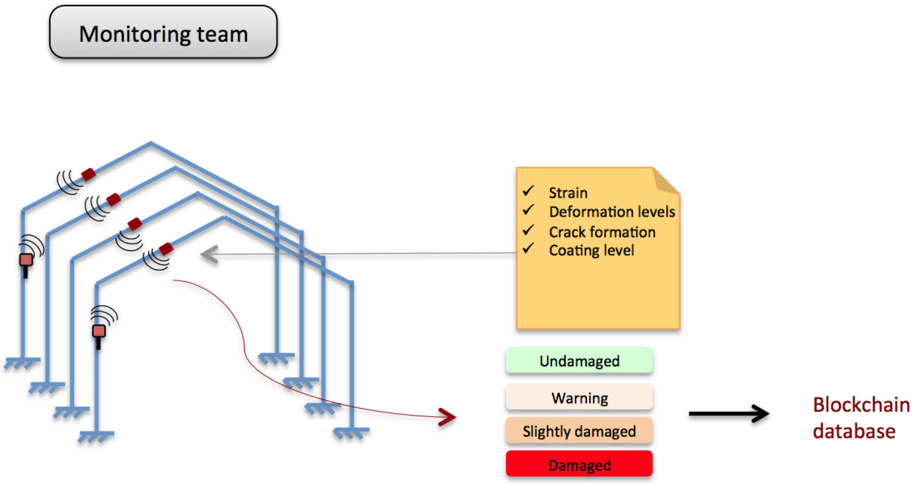


Figure 4.7. Illustration of the information registered during the O&M phase

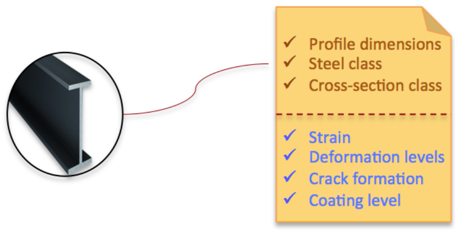


Figure 4.8. Element's information at the end of life

Figure 4.9 summarizes in a flowchart the stored information during the different phases of a project. In addition, it shows from which actors information originates. More specifically, as it was described above, the information related to BIM would be inserted by the structural engineer and the construction manager during the design and construction phase respectively. During the monitoring with the sensors and depending on the selected sensor-reader relation different scenarios can occur. If it is desired that everything are conducted automated, then there should be installed enough readers in the proximity of the sensors to achieve that. Otherwise the sensors that remain unreachable should be read by the facility operator. Finally, the monitoring team is what connects the measured data from the sensors with the blockchain database. They will supervise the data and approve their insertion to the blockchain database.

Last but not least, a fourth box can be also considered in the information flow of Figure 4.9. That would be the continuation of the information and its insertion back to the BIM model. However it is not depicted because it has not be thorough and in detail described in the present study. Nevertheless, as it was mention in 4.2.2.1 the transactions recorded in the blockchain database, if it is desired, can be exported and stored in a third-party cloud. This could be in our case BIM. Having exploited the security and the transparency that is offered by the blockchain technology and that such a process requires then insert the recorded information back to the BIM model in order to have everything gathered in one place.

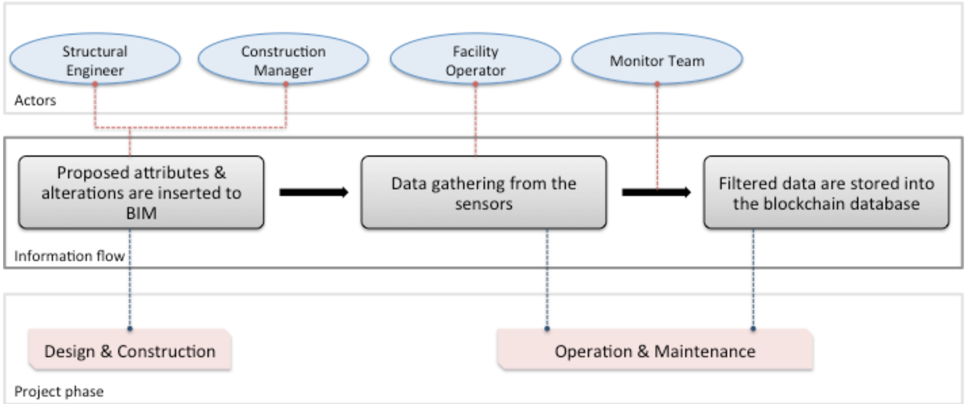


Figure 4.9. Flowchart of the gathered information

# CHAPTER 5 – ASSESSMENT

*This chapter contains the findings of the validation procedure. At the beginning of the chapter the difference between a validation and an evaluation is explained and then the validation method that is selected for this study is stated. Before the final section where the findings are presented, the set-up of the interview procedure as well as the background of the interviewees is specified.*

## 5.1 INTRODUCTION

Following the methodology described in chapter 2, this would be the last step of the study where the validation would be held. It is usually observed in design science that validation is getting confused with evaluation, however their differentiation is explained in several studies (Wieringa, 2014; Pefferes et al., 2007). Evaluation's purpose is to check how the artefact will interact when applied on a real world project and whether a new iteration cycle of designing is needed (Wieringa, 2014; Pefferes et al., 2007). On the other hand, a validation procedure is conducted before the actual implementation on a real project, to examine if the suggested artefact addresses sufficient the initial problem, if the requirements set for treating the problem have been met and if it positively contributes to the stakeholders' needs (Wieringa, 2014). In the latter case of validation assessment, the artefact has to be tested and criticized thoroughly before a real implementation, hence it has to undergo a simulation that will assess whether it is sufficient for a further application (Wieringa, 2014).

Venable et al. (2012) also refer to the differences of validation and evaluation by using the terms ex ante (or formative) and post ante (or summative). An assessment conducted on a not fully developed artefact before its implementation on a real project is called ex ante, while an assessment on a complete designed and developed artefact that is conducted during its implementation on a real project is called post ante (Venable et al., 2012). A brief comparison of the two can be seen in Table 5.1 with ex ante the right one for this study.

Table 5.1. Comparison among an ex ante and a post ante assessment (Venable et al. 2012) (own illustration)

| **Ex Ante** | **Post Ante** |
|---|---|
| Formative | Summative |
| Lower cost | Higher cost |
| Faster | Slower |
| Assess design or prototype | Assess instantiation |
| Less risk to participants | Higher risk to participants |
| Higher risk of false positive | Lower risk of false positive |

In more detail, the main goal of a validation is to investigate the effectiveness of the proposed artefact regarding the described problems. There are five additional secondary goals that a validation might examine. First, if the requirements of the "treatment" are functioning. That is connected with the second goal, which is to assess if the selected methodology (design science) successfully contributes to the study. Third, what news does the artefact bring compared to existing ones, fourth if by applying the artefact unintended side effects might occur and last one is to come up with suggestions for further improvement (Venable et al., 2012; Johannesson & Perjons, 2014). Depending on the validation, the above-mentioned goals could either be covered all or some of them (Johannesson & Perjons, 2014).

To simulate and test a theory, several possible research methods exist and can be used like surveys, focus groups, case studies etc. One of the simplest methods that does not require remarkable resources and can be done in a short period of time is by interviewing experts (Wieringa, 2014; Lucko & Rojas, 2010; Venable et al., 2012). Experts role is to examine the artefact, understand how it works and predict if it meets the requirements and improves the initial problem context (Wieringa, 2014). If not, then a new iteration of the design cycle should take place and further improve the artefact; before it is implemented on a real project. In this study the validation method with expert interviews was considered to be the most suitable and the one that is deployed.

Expert interviews consider to be an effective means for testing an artefact, however despite their ease and quick implementation, there are also some potential drawbacks that should be mentioned (Wieringa, 2014; Johannesson & Perjons, 2014). Firstly, the risk that the interviewee might not understand completely or in depth how the artefact works, hence they might not give solid feedback and predictions on the artefact's application. A way to prevent this from happening is to ask experts questions which involve more practical aspects to their answers and describe the logic behind their suggestions as well as include some questions regarding the mechanisms of the artefact (Wieringa, 2014). Another risk is the false positive answers. Because interviews are person to person communication, it is very often that experts might withhold their comments and be less severe on their judgement than they would like (Johannesson & Perjons, 2014). What is more, positive comments might even be less desirable than negative ones. Positive comments are necessary though, otherwise the artefact is considered unsuccessful, however there should also be negative ones because those are the useful ones which will help in the improvement of the artefact. In addition, negative comments could designate and reveal aspects that the research hasn't considered yet (Wieringa, 2014).

## 5.2 Validation Procedure

*Semi structured interviews*

Interviews set up for validation usually follow two types, they are either structured or semi-structured. A structured interview has predefined questions, no follow ups are allowed and they have a specific order that cannot change. It is similar to a survey or questionnaire with the difference that it has open questions. A semi-structured interview has also a predefined set of questions, however they are asked in the form of a dialog with additional and follow up questions coming up based on the flow of the conversation. Also, the order of the questions is flexible without having a mandatory strict structure of addressing them. For a qualitative study such as this one, semi-structured interviews are more suited since this a less restricted way of interaction would provide more rich feedback.

*Interviewees Background*

Four people from the industry agreed to participate in the validation of semi structured interviews with each interview lasting for about an hour. There were two main criteria behind the selection of the people. The first one was to possess sufficient knowledge about the technologies suggested in the framework as well as have adequate knowledge with steel structures. The second criterion was the interviewees to have a good seniority level, an amount of at least 6 years of experience in the sector was set. An overview of the interviewees focus area, position and years of experience is displayed on Table 5.2.

Table 5.2. Interviewees characteristics

| *No* | *Position* | *Years of experience* | *Expertise on* | | | |
|---|---|---|---|---|---|---|
| | | | *Steel structures* | *BIM* | *Blockchain* | *Sensors* |
| *1* | Structural engineer | 6 | High | High | Low | Moderate |
| *2* | BIM Coordinator | 11 | Moderate | High | Moderate | Moderate |
| *3* | Digital transformation manager | 11 | High | High | High | Moderate |
| *4* | Director | 20 | High | High | Low | Moderate |

*Procedure*

At the beginning of the interview procedure each participant (researcher and interviewee) gave a brief introduction regarding their background. Then the researcher proceeded to a presentation of the study objectives with a focus on the parts that the interviewee will be requested to provide feedback. The questions were formed with the intention to cover all aspects of the framework and the technologies that constitute it. Three themes were formed, each one consists of questions related to a different technology (i.e. BIM, sensors, blockchain). At the end there were two overall type of questions. The complete scheme with the questions and follow-up questions can be found in Appendix C.

## 5.3 FINDINGS

In this section the findings of the expert interviews would be presented in the three technological themes and according to the sequence they were asked. At the beginning of each theme it is briefly described what was answered by the four experts as well as involving their positive, negative or recommended comments. At the end of each theme a SWOT table will summarize the strengths, weaknesses, opportunities and threats that came out from the interviews regarding the respective theme.

*BIM*

When the brief presentation regarding the study is over, most of the experts shortly expressed their first impression and then the semi-structured interview started. The first four questions of the interview concern BIM and its efficacy in the present study.

All four of them were experienced with BIM and recognize the fact that its implementation is constantly growing in the industry. Especially large companies with demanding and large-scale projects are increasingly integrating BIM into their practices. The impact of working on a 3D model containing all the necessary information and to be used as an information sharing platform with other actors involved in a project was highlighted. Moreover, experts agreed with the proposed attributes (namely, material property, type of steel element, element connections, assembly information, location, element strain) to be registered on a BIM model during the design and construction phase and consider them as essential for the reuse of steel elements. All the above attributes where considered beneficial for the process.

Some attributes were praised more than others, for example, the sequence of installing each element was considered very useful as it not only reduces the risk of accidents and mistakes but also makes the whole procedure more precise and faster. Furthermore, the deconstruction procedure will be benefit as there would be an indication about the order and the overlapping of other involved materials and elements. Based on this, it was also suggested that by using BIM, deconstruction steps could be made even clearer by being visualized on a 3D model and even represented in an animated form. Another attribute that stood out was the importance of having an overview of the type of connection between steel elements. They agreed that it is of benefit to know if there is a bolted or a welded connection since in the latter case the length of the element will be reduced compared to the initial as it has to be cut for removing it. In extension to that, an extra recommendation was made to include any extra details in the connections such as steel plates in between the connected elements or a locally customized supporting steel.

One of the objectives of the interview was to receive expert's recommendation and suggestions for improvement of the framework. Towards that, the interviewees proposed several ideas to be taken into consideration. A main suggestion was the attachment of a unique code to each element, so as to create an identity containing all other information. Other recommendations concern the addition of extra information regarding the age of the elements and their origin, that would be achieved by involving the element's date of manufacture as well as who the supplier is.

Finally, experts expressed their uncertainty regarding some aspects of this part of the framework. The first aspect has to do with one of the registered attributes, a technical detail, the display of each element's load value. It is not feasible in the form of just one number, because there are many different types of forces acting. What can be added instead is the display of the range of that quantity. This could be a useful piece of information showing what forces acted during, for example, a 30years time period and it could be even more useful if the element would be reused for a second time. That would lead in a database indicating an overview of the acted forces during the first round of its usage as well as the second round and so on. Another point of concern is the extra effort that is required for inserting those details which might take some extra time and raise the total cost. Hence, this should be the asset owner initiative and he should be determined towards applying a circular solution.

Table 5.3. SWOT of expert's comments regarding the BIM part of the framework

| STRENGTHS | WEAKNESSES |
|---|---|
| • Established technology in many companies and gradually growing even more<br>• Software that can facilitate such a task exist<br>• Further include: steel element manufactured date and supplier details<br>• Describe element' s connection in detail | • Registering element' s load does not add value at the design phase, especially if it will be monitored more specifically in the O&M phase |
| **OPPORTUNITY** | **THREATS** |
| • Visual (animated) representation of deconstruction<br>• Set the basis for creating a "passport" for each steel element | • Extra time for registering those attibutes. Will it be cost-benefit? |

*Sensors*

After discussing the part of BIM in the design and construction phase, the next three questions to the experts concerned the operation and maintenance phase and the use of sensors for maintenance purposes as well as for collecting data of elements that can be exploited for a reuse strategy.

In principle expert's opinion regarding sensors is that they are of added value. Specifically, during the last several years they are employed more and more and at the same time their prices keep decreasing. However, they have mostly encountered them in large scale structures such as high-rises, stadiums and bridges; on element level but also in specific spots or corners of a building measuring characteristics of the building as a whole (like settlement, rotation etc.). Nonetheless, they agreed on the necessity of monitoring also for safety reasons as there are many cases where damages or even collapse could have been avoided. On top of that, a specific instance brought up by one of the interviewees confirming the necessity of maintenance data in structures of the public sector. As he pointed out, public sector currently lacks maintenance data regarding replacements, repairs, removal, inspections of elements or in case they possess for some structures they are not well organised.

So far sensors and visual inspections are the main means used for structural health monitoring. Experts support that in cases, for example, of large structures with multiple elements to be checked and with a high inspection frequency it is not viable to rely on human resources since it would require much more time and that wouldn't be efficient. Hence, in such cases sensors are definitely necessary.

As mentioned in chapter 4.2 there are multiple sources that may impact a structure's condition (e.g. environment, earthquake, fatigue, settlement, nearby activities, vibrations etc.) and cause a number of different characteristics to surpass their limit values as well as be measured by sensors. Interviewees agreed on the proposed characteristics but they suggested focusing on two as more important, deformation and strain. Moreover, they agreed with the idea to measure those characteristics on certain elements that are more critical and prompt to present some sort of problem instead of a larger number of elements. They further recommended to include in the critical elements those that are in the exterior of a structure since they are constantly exposed to the environment and weather conditions.

Some other minor recommendations addressed the importance of properly defining the sensors with each element. Make clear which sensor belongs to what element by assigning it to the BIM model. What is more, another issue discussed was when is the correct timing of installing the sensors. Two completely opposite opinions were given by two of the interviewees. One of the experts was in favour of installing them when a damage occurs or when there is suspicion about an upcoming problem while the other one believed that it is important to install straight from the beginning to capture everything from the start.

Table 5.4. SWOT of expert's comments regarding the <u>sensors</u> part of the framework

| STRENGTHS | WEAKNESSES |
|---|---|
| • Necessity and urge for monitoring during the O&M phase, especially in large scale buildings and structures<br>• Exterior elements should be measured | • Requires extra cost for installation experts<br>• Not common to be used in conventional buildings<br>• Not many AEC companies acquainted with sensors |
| **OPPORTUNITY** | **THREATS** |
| • Current momentum in sensors technology regarding AEC<br>• Reliability and safety increased<br>• Capture all data from the start of a building' s service life | • Not convinced if despite the low cost of the sensors, will in total, including the setup, be cost effective<br>• Properly indicate which sensor belongs to which element<br>• Decision on how many and which elements should be monitored |

*<u>Blockchain</u>*

Towards the end of the interviews two of the last questions concerned the application of blockchain in the AEC industry. At the beginning the importance (or not) of secure and transparent databases as well as their preference (or not) of the existing once and then their view on the suggesting system was explained.

All of the interviewees support the idea of a more transparent, secure and immutable database system; however, half of the experts were reluctant regarding its usage on a potential future steel project since they are satisfied with how things currently operate and consider the whole procedure of a transition to a new system troublesome. The other two interviewees also agree on the difficulties to adopt a new system but on the other hand they add that traditional databases also have weak points and there is room for improvement, especially with regards to the above mentioned aspects of security, immutability and transparency. In fact, one of the interviewees mentioned that in the company he is currently working, they keep investigating and try to improve security aspects in the existing database system since storing and sharing information need to be safeguarded in the best possible way. It was further mentioned that having a system with immutable and accurate data of elements will enhance the markets which sell used steel elements as well as drive for the creation of new ones.

Regarding the feedback on the structure of the suggested blockchain database, there were both positive as well as cautious comments. The positive ones came from the idea to avoid registering on a live feed basis and every single detail but instead register only those information that surpass certain limit values and are critical for the elements. While the cautious ones concern the usability of those data after a period of, for example, forty years and if they would be readable and manageable by then.

Overall, they recognize the hype and the trend around blockchain that started from the IT sector and later expanded in other sectors as well, and they see its dynamic in the AEC industry. However, they believe that it needs some years of applications in order for its full extent to be perceived. More precisely, it could be implemented on real projects then compare it with similar projects based on a traditional database and after that decide more carefully about its added value.

Table 5.5. SWOT of expert's comments regarding the blockchain part of the framework

| **STRENGTHS** | **WEAKNESSES** |
|---|---|
| • Increase transparency, security and immutability of the data | • Requires time for companies to get acquainted<br>• AEC sector not open to innovation and to easily adopt new digital technologies<br>• Settled and confident with the current traditional databases |
| **OPPORTUNITY** | **THREATS** |
| • Enhance markets that sell (re)used steel elements by providing reliable information<br>• Presented functioning concept<br>• Channel the data afterwards into BIM | • Relatively new technology, unknown in the AEC<br>• Would access in the data after many years be possible?<br>• Application on a real project and then compare with a tradition database |

Finally, it was asked to share their view on the framework as a whole and indicate if they found any strong or weak points in it. In general, the comments it received were positive regarding the part of BIM and the required attributes to be registered during design and construction phase. Moreover, the sensor part received supportive comments because apart from enriching maintenance information with frequent and reliable data which can be exploited after the end of life of the structure it also increases safety. Regarding the blockchain database they welcomed the initiative and the structure of it however they want it to see it being tested over the years like every new technology. As a potential drawback they commented on the added cost that might occur by employing BIM and inserting all those attributes or by getting acquainted with a blockchain database. However, they recognize the long-term potential of it and that people might not notice a direct impact but they need to be convinced that acquiring all this information will create a profit later on.

*Overview*

In general, all four experts showed their interest in the content of the study. They were more positive regarding the ultimate outcome of the study, which serves the concept of circularity and, more precisely, the reuse of steel elements as they find it an attractive idea with room for improvement. They further connect it with an increasing tendency of companies and clients towards adopting circular solutions. The other aspect of the study which receive positive comments was the use of BIM during the design and construction phase. The proposed characteristic to be registered on the BIM model was agreed by the experts to be useful and sufficient nonetheless they additionally suggested a few more to be considered. Sensors and blockchain technology were discussed, overall, in a moderate to positive way. However, they are technologies that are not used in the building industry, especially blockchain and it was more difficult for them to comment whether such a solution would applied and established in the sector.

## 5.4 FEEDBACK INTEGRATION AND RECOMMENDATIONS

In this section the feedback received from the experts as well as their recommendations will be discussed. By analyzing the feedback as presented in the SWOT tables it was noticed that the comments can be divided into tangible comments that can be directly adopted in the framework and into more theoretical ones in the form of advice or concerns. The former will be summarized below through the strength, weakness, opportunity, threat of SWOT while the latter would be mentioned in the recommendations and limitations.

*Strengths*

- According to SWOT, strengths are elements of the framework which work well and it would be beneficial to build upon them in order to reach and accomplish the suggested opportunities. More specifically, some of the strengths under the BIM SWOT where not initially included in the framework and where suggested by the experts as elements that would add value to it. Those are the "steel element manufactured date", the "supplier's details" and the "details over elements connection". They are tangible improvements of the framework and they could be adopted by the design team during the design and construction phase.

- Strengths under the sensor SWOT, confirm the added value of monitoring during operational and maintenance phase and especially for large scale structures. Furthermore, it is also highlighted to select among the monitored elements those on the exterior of the structures.

*Weaknesses*

- Under the BIM SWOT experts suggested to discard registering the range of acting load from a structural engineering analyses since it is complicated and it would not contribute especially in case of monitoring during the O&M phase.

*Opportunities*

- Taking advantage of the registered data such as elements connection details, it was suggested by the experts under the BIM SWOT, and as an opportunity, the potential of creating a visual (can be even animated) representation of the deconstruction of the building. That would smoothen the procedure, make it more accurate and protect the steel elements.

- Under the sensor SWOT it was mentioned the opportunity and the urge of start measuring from the start of building's operation in order to approach the element's realistic situation as possible.

- Under the blockchain SWOT it was discussed with one of the experts the opportunity of having the imported data on the blockchain database during the O&M phase, exported when necessary and connected into the BIM model.

*Threats*

- A threat identified under sensor SWOT that should be taking into consideration is the proper (digitally) assignment of each sensor to the respective element in order to have aligned, accurate and exploitable measurements.

An overview of the experts recommendations about the framework that are tangible and could be applied after this validation:

➢ During the design and construction phase:

| *Include* | *Discard* |
| --- | --- |
| ✓ steel element manufactured date | ✓ the attribute of load range |
| ✓ supplier's details | |
| ✓ details over elements connection | |

➢ During the operational and maintenance phase:

*Include*

✓ prioritize monitoring of external/peripheral elements
✓ data if desired could be imported into BIM

Finally, in Figure 5.1 the updated version of the framework can be seen including the suggestions of the experts.

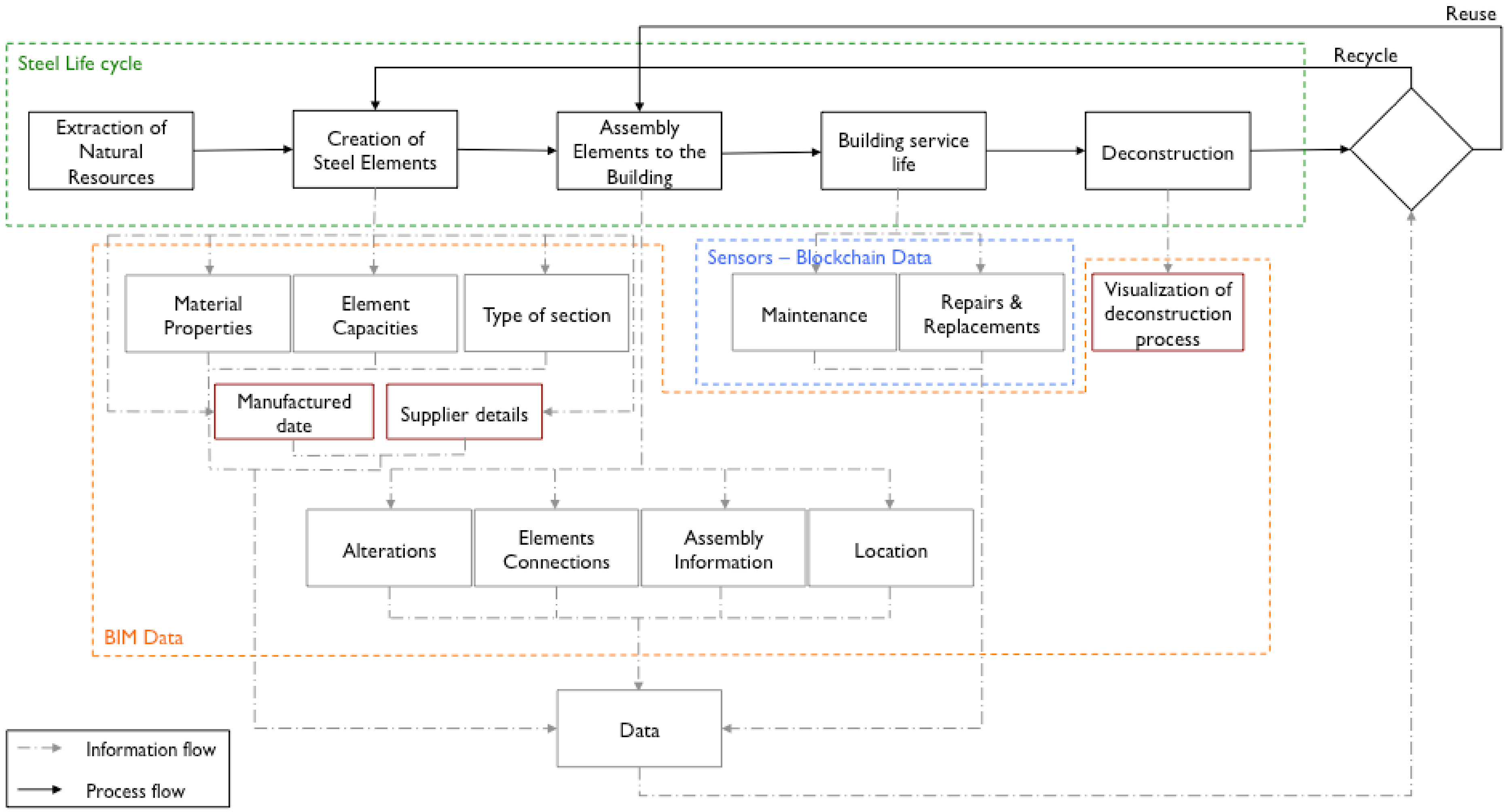


Figure 5.1. Updated version of the framework including expert's suggestions

# CHAPTER 6: CONCLUSION

*On this final chapter, a summary of the study is presented, by providing a response to the research questions. Moreover, in the next section the limitations that this study faced are stated, then the recommendations of this study and finally a reflection both scientific and societal relevance as well as personal.*

## 6.1 ANSWERING THE RESEARCH QUESTIONS

At the beginning of the thesis, along with the scope of the study, the main research question and the four sub-questions were stated to complement and frame its context. The main research question represents the main objective of the study while the sub-questions add the required details to supplement it and also create the stepping stones for answering it. Those were answered in detail through the previous chapters of the study. In this section, both the main questions and the sub-questions will be concisely answered.

1. What is the current reuse situation?

To better describe the current situation of a steel reuse strategy someone has to take into consideration (i) the three different types of reuse, (ii) what is the procedure followed from the end of life until the reuse of a steel element and (iii) the intermediaries involved actors. At the beginning the three main types of which steel reuse occurs were stated, then a typical procedure was explained as well as the role of the involved actors. Finally, the problems of steel reuse from an information management point of view were pointed out.

After a thorough literature review (section 3.2), steel reuse occurs under three different circumstances; the first one is when a building needs to be relocated, the second when a building is getting rebuilt in the same location (in-situ) and the third when a building is reaching its end-of-life (or is after it, i.e. abandoned) and its elements can be used as a source for the construction of a new building. The steel elements which are of particular interest for reuse and to which this study refers to, are the beams and columns, while the structures that offer such elements are workplace buildings, warehouses, factories (without fireproof) and any other similar steel manufactured structures.

Under all three circumstances, the necessity to have proper information over the condition of steel elements after (and during) their service life remains. What also contributes to that is the poor digital technology that is used in the AEC industry. Specifically, in the case of reuse this is translated into not keeping a clear and organised digital record of designs, materials and other valuable attributes leading to uncertainty regarding the quality and condition of the elements. Currently to assess whether an element can be reused several actors are getting involved to extract this information. For example, actors like fabricators, material dealers and service centers are collecting and transporting facilities in order to apply different destructive and non-destructive methods to evaluate their status. This expands the business network as well as raises the total cost of the procedure.

2. Which symbols, symbol properties and relations between symbols in a typical BIM model contain usable information for steel reuse?

*What is a BIM symbol & Which symbols*

Symbol is a novel way that BIM introduced for modeling in comparison to the linear 2D CAD system. Instead of drawing an object with lines, the objects already exist in the software's libraries and they are inserted as a whole. A symbol can represent an element, a space or even void. The main feature that symbols have, apart from the modeling characteristic, is the ability to assign on them any kind of information. The symbols that concern this study are the beams and columns. More specifically the additional properties and attributes that can be assigned to them during the design and construction phase.

*Symbol Properties*

The symbol properties that are suggested to be registered are presented in the Table 6.1 below.

Table 6.1. Properties inserted to the BIM model

| PROPERTIS | DESCRIPTION |
|---|---|
| **TYPE OF STEEL ELEMENT (CROSS-SECTION DIMENSIONS & GEOMETRICAL VALUES)** | Steel elements are distinguished by the different standardized cross-section profiles that they have. For instance, I-type profile or H-type profile as well as many different others. From this several other important attributes derive, such as, cross-section dimensions and some geometrical values. |
| **MATERIAL** | In this property the grade of the steel is filled in. When an element is examined whether it is good for reuse and that characteristic is missing then testing needs to be conducted which will lead to extra costs. |
| **ELEMENT CAPACITY** | Knowing the maximum capacity (e.g. moment or shear) will help decide whether the element can be reused and bear the loads of the new intended structure. |
| **ASSEMBLY** | This may include information about the sequence in which the elements were assembled, steel connections that may need to be removed or the weight of each |

| | |
|---|---|
| | element. That way the disassembly and lifting would be better facilitated. |
| **LOCATION** | The attribute of location of the building should also be registered in the elements. It would be useful for future decisions regarding the dismantling elements and the selection of the closest fabricator, storage place or recycle center. Based on this, the distance of the structure from the potential facility can be measured and help in the decision making taking into consideration transportation costs as well as environmental burden of each choice. |

Relations between symbols

BIM provides the possibility to describe and display the relation between elements. More specifically, information about the connection of elements, like “beam to beam” or “column to beam” would be registered which could have an added value at the deconstruction phase. When aiming for reuse, a connection with bolts is preferred over a welded connection. In the second case the element will have to be cut and therefore lose part of its length as well as add extra effort by the deconstruction crew. Another essential relation is that of steel elements with different components. BIM’s interoperability offers the possibility of having an overview of different parts of the model, such as the architectural, the structural or the MEP (Mechanical, Engineering & Plumbing). This would help to detect the interaction and any potential anomalies among steel elements with other components which would eventually assist in better prioritizing the deconstruction sequence.

3. Which additional information should be collected in the life cycle of a building? (section 4.2)

Apart from the design and construction phase, additional information that derive from the operation and maintenance phase of a structure are also very important. A structure which is exposed for decades in operational and environmental loads is inevitably going to present signs of deterioration like fatigue, corrosion etc. Hence, the collection of data of steel elements condition throughout a structure’s lifecycle is a required process to cope with those changes. The existing applied practice of maintenance through visual inspections faces several shortcomings such as the high dependence on the maintenance crew’s experience and efficiency as well as the frequency of inspections. Sensors on the other hand can provide accurate quantitative data over different characteristics and with whatever frequency is needed in each case. Therefore, sensors will monitor and measure the selected characteristics which later on would be registered on a database based on blockchain technology.

4. How can the above information be safeguarded with blockchain technology?

In the present study blockchain technology is applied as a database which stores transactions. The recorded transactions occur after a specific procedure of the collected data from the sensors. Sensors measure certain characteristics that are selected by the maintenance team. Moreover, a threshold value of those measured characteristics is defined. When a measurement of a value surpasses the defined threshold value then an event is created and is recorded as a transaction to the blockchain database. Once the value is recorded in the database it means that a new block is created, it is timestamped and it contains the id of the steel element as well as its recorded value. Based on the fundamentals of blockchain technology (explained in more detail in section 3.3), when a block is added to the chain then it is immutable and it cannot be subjected to any kind of alteration or being removed, users have only the read option. This provides transparency, trustworthiness and reliability to the stored data.

*Main research question*

***How can information technology (BIM, Blockchain, sensors) enhance the reuse of steel elements?***

The main research question expresses the motivation for this study and its answer lies to the answers given in the above subquestions. The ultimate goal of the study is to provide a framework based on three main features that would enhance circularity in AEC and specifically in steel structures. Firstly, it is suggested that for the specific task of reuse, the selection of BIM as a design and information management tool from the early phase of a project is necessary. By that, valuable information regarding steel elements would be defined, organised and gathered in digital form in one place so it can be exploited when deemed needed in the future. Furthermore, BIM's interoperability could help later on when a building reaches the end of life. For instance, it could easier organise and coordinate the logistic aspects as well as the communication and the sequence of actions of the involved actors, such as the demolition contractor, the maintenance group, the client and the potential buyer of the used steel elements. Subsequently, as a second main feature of this study, it is suggested that all the gathered information in the design and construction phase, could be supplemented with extra information regarding the steel elements during the service life of the structure (Operational & Maintenance phase). This could eventually create a thorough identity for each element by possessing both its characteristic manufactured data and those occurring throughout its operation life. To ensure the integrity of the collected data during the O&M phase an alternative database for storing the measured data was suggested, i.e. based on blockchain technology. Having a database based on blockchain technology renders immutability of data, transparency and security. The third feature of the study comes to explain how the measured data are linked and inserted to the database. IoT and sensors would play that role of an intermediary tool to complement the blockchain database. Sensors would measure, depending on the case, the desired attributes which would then supply the database with accurate and consistent data throughout the lifecycle of the structure. A schematical overview can be seen in Figure 5.1 of the fifth chapter.

## 6.2 LIMITATIONS

This section contains the limitations that this study took into consideration while it was conducted.

1. The first limitation concerns the methodology. Design Science's methodology full version, undertakes two additional steps after the validation. Those of implementation on a real project and then its evaluation. Considering this study as part of a master's program this option wasn't viable and so the shorter version was followed. Hence, this study constitutes a good starting point, however in order to generalize its findings an application on a real project as well as an evaluation has to be conducted.

2. A second limitation concerns the validation interviews. Even though their responses included both positives and negative comments, there are always interpersonal aspects which entails a possibility of being softer and subjective on their comments in contrast with other less personal validation methods.

3. A third limitation constitute the cancelation of an internship with a company due to the uncertainty involved during the first few months of the pandemic. A potential cooperation with a relevant company might had speed up the first stages of the study. For example, by conducting exploratory interviews or by having access to some of their reused cases would led to faster familiarize with certain aspects of reused projects.

## 6.3 REFLECTION

With this final chapter of this study the intriguing journey of Construction Management & Engineering master comes to an end. The chapter will be divided into three parts. First, the reflection of the study to the scientific community, then to the society and finally a retrospective reflection of myself during the whole procedure of the master thesis.

### 6.3.1 SCIENTIFIC

It was observed that scientific studies about steel reuse were very limited despite the benefits that could generate and despite the announcements by EU or other global organizations for new strategies and measures towards an increased circular economy in the AEC. Most of the publications were scattered the previous 15years and with many of them being very short conference papers with limited content. This study attempts to point out and organise what information should be stored in every phase of a project in an effort to promote and wider adopt steel reuse. To achieve that, steel reused elements have to be technically-wise proved to function and at the same time economically competitive to buying recycled or new steel in order to constitute a viable option. Based on the proposed registered attributes a steel element after a building's end of life will contain every relevant information about its condition and specifications. By that apart from a more holistic view over the elements reliability there would also be a financial and environmental benefit from removing intermediaries actors for testing, refurbish and transport the elements.

Another aspect that was attempted to scientifically contribute is the introduction of blockchain. The last few years several studies started to investigate about the positive impact that blockchain technology could have in the construction sector (i.e. Li, Greenwood & Kassem, 2019, Nawari & Ravindran, 2019, Perera et al., 2020). This study comes to add on that effort by suggesting a blockchain database for storing data measured from sensors and require a transparent, secure and immutable platform to be stored. Hence, blockchain comes as a tool to safeguard the integrity of the recorded data which is of great importance if the steel elements if they would ultimately be reused on another structure

### 6.3.2 Societal

The underlying societal impact is that steel sector would eventually climb even higher the circularity ladder and start shifting from the dominant recycle strategy to reuse. As explained, by shifting from recycle to reuse would save substantial amount of energy and $CO_2$ emissions from melting and reformulate the steel. On top of that, as mentioned earlier after the end of life some intermediary actors might not be necessary which can have both positive and negative societal outcome. Positive due to the less environmental footprint from the fewer refurbish and testing processes as well as transportations while negative due to the shrinkage of their field of work. However, it may also create a new business opportunity by establishing a platform which will contain information of steel elements from buildings that have either reached their end of life or it is known when they will reach it. So for example someone could eventually buy an element that is currently in use but its availability along with its exact specifications in known beforehand. Lastly, by following the framework and with proper information management then theoretically steel elements could potentially reused more than one or two times, extending that way significantly their life expectancy.

### 6.3.3 Personal self-reflection and lessons learned

After a long journey, longer than expected to be honest, this thesis comes eventually to an end. Although it lasted that much, it was a beneficial experience with many lessons learned in academic as well as in personal level.

The fact that I got the opportunity to conceive and develop my own research topic was very important because I worked on something tailored to my preference. Steel elements was where I specialized during my bachelor and is a part of civil engineering projects that attract me the most. On the other hand, circular economy, BIM and IoT were concepts introduced to me during several courses of TU Delft and really fascinated me as well as triggered my desire to further delve into them.

I believe that I obtained a lot of valuable lessons right from the first days of the process. I had to learn how to organize my ideas and the content found in different articles, learn how to make it more concise and formulate a presentation in order to make it accepted by not only the graduation committee but also from people from the industry. During the first months of the thesis, which fell under the first months of the covid pandemic, I got myself familiarized with several companies of the AEC sector of Netherlands as I communicated and attempted to organize a cooperation with them for my thesis. Unfortunately, only one of my attempts was fruitful but lasted only for a short period of time since companies were hesitant on hiring during those uncertain times. This was a rejection that I had to handle, learn from it, for example consider if there were also other reasons except for the pandemic for not continuing our cooperation, and bounce back.

Furthermore, the research itself was another lesson. Learning how to cope with high level academia standards by having to manage and structure my own report as well as getting to study many articles, books and journal articles while learning how to identify what is useful and what isn't. Apart from that, I learnt how to conduct a semi structured interview, how to formulate questions and how to be prepared with follow up questions in case of short responses or the need for more information to be extracted from an interviewee.

## 6.4 RECOMMENDATIONS

In the first part of this section a brief overview of the recommendations and concerns that arose during the validation procedure with the experts will be presented while in the second part, recommendations for future research will be mentioned.

*Positive*

- Despite the main intention of the study towards information management some other aspects such as reliability and safety of the structure were also enhanced. Since some elements would be monitored and there would be a precaution system structural safety would be always updated.

*Barriers*

- One of the main concerns addressed by the experts was regarding the extra costs that would occur for example by the extra required time and effort for registering the suggested attributes. This was listed as a threat to the framework since most companies in AEC are used to cutting down costs and do not take into consideration the long term opportunities.

- Blockchain technology is particularly recent technology and unknown in the construction industry. It would require a lot of effort to persuade a conservative sector such as AEC for the benefits it could bring and for a potential adoption of a new technology like blockchain until it has been thorough explored and tested.

- Companies mainly working on conventional buildings are aware of sensors however they are not acquainted with them, thus they might be hesitant about their contribution and their added value especially taking into consideration their cost effectiveness.

*Future research*

- As a continuation of this study it would be useful to explore what happens during the deconstruction phase of the project and even after that. Hence, that might be served with a life cycle cost (LCC) analysis comparing recycle and reuse after the end of life. In addition to that, it would also be useful to investigate how will the logistic aspects with storing and distributing the reused elements work as well as would be the new involved actors.

- As it was observed during the literature review regarding the sensor technology, in most of the publications the distance between the sensor and the reader was selected to be the minimum possible despite the capability of the sensor to reach larger range. So the aspect of the range was not examined. Therefore, a study which would contain a steel element set up and sensor-reader range at their maximum distances could be investigated.

# APPENDIX A: SENSORS

In this section a few more details about sensors and rfid technology will be presented. More specifically, typical RFID sensor – reader set ups for measuring different characteristics will be displayed as well as RFID sensor and tag relation in more detail. Those information were acquired from published articles and in order to be more comprehensible some screenshots of them were also included.

- Force/Displacement monitor case study by Zhang et al. (2021)

In their research they monitor the tension of a steel beam with wireless passive sensors based on RFID. Their overall objective was to examine whether this sensor system could be used in order to monitor whether the tension force surpasses a certain threshold (i.e. enters the non elastic area). To achieve that, they test the rfid sensor system and compared it with measures from a different sensor with cables.

In this configuration, the sensor and the tag were combined. The sensor technology was a multistage breakage-triggered strain sensor that entails a brittle fracture part that tracks predefined limit values strain levels. The physical deformation is translated into electrical signals and then communicates with the reader. Figure C.1 show a close up view of the sensor. Figure C.2 shows the wireless connection of the reader with the tag/sensor, however in the laboratory test that they conducted the reader was at a fixed distance of 0.6m.

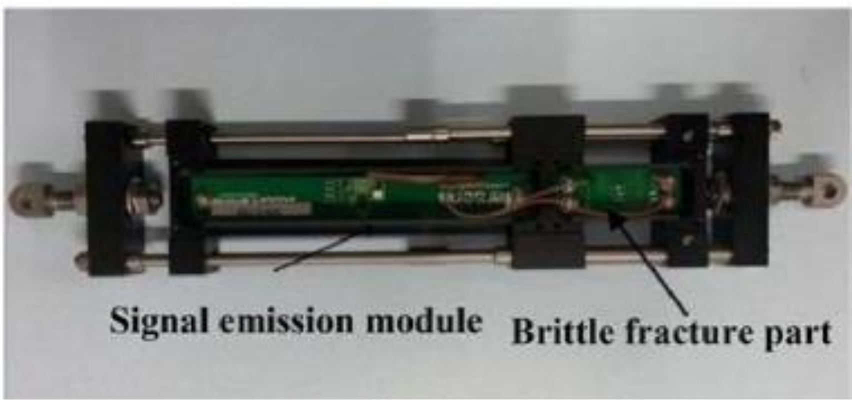


Figure C.1. RFID sensor/tag

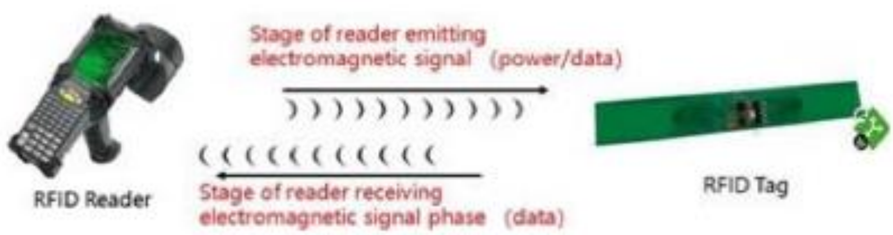


Figure C.2. RFID system

- Crack detection and strain measurement case study by Li and Wang (2020)

Li and Wang tested a hybrid passive/active RFID sensor for crack detection and strain measurement. The main (passive) sensor/tag can be seen in Figure C.3 and it contains the antenna and a chip. In their study they extent the passive sensor by adding a cell battery and a solar cell so that the sensor can also operate as an active sensor when it absorbs solar energy increasing that way its distance from the reader (Figure C.4). Figure C.5 shows a design of the whole set-up, including the reader and he sensor.

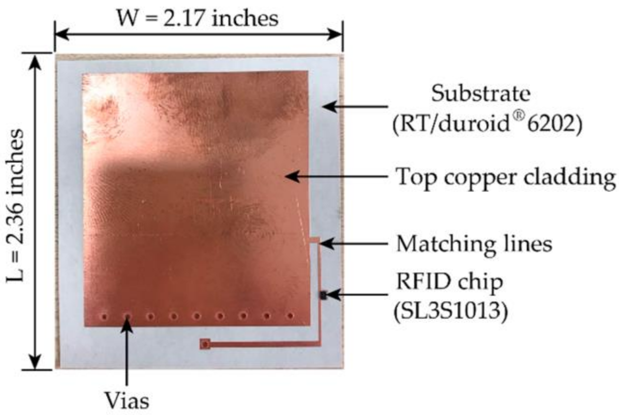


Figure C.3. Passive sensor

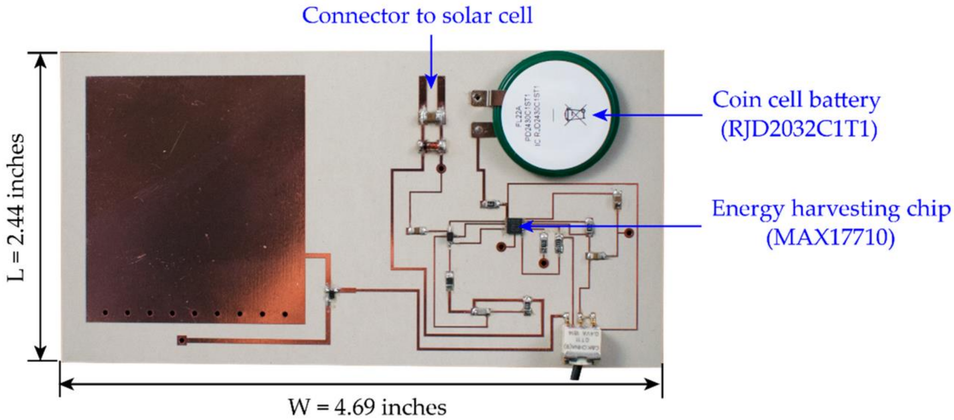


Figure C.4. Hybrid passive-active sensor

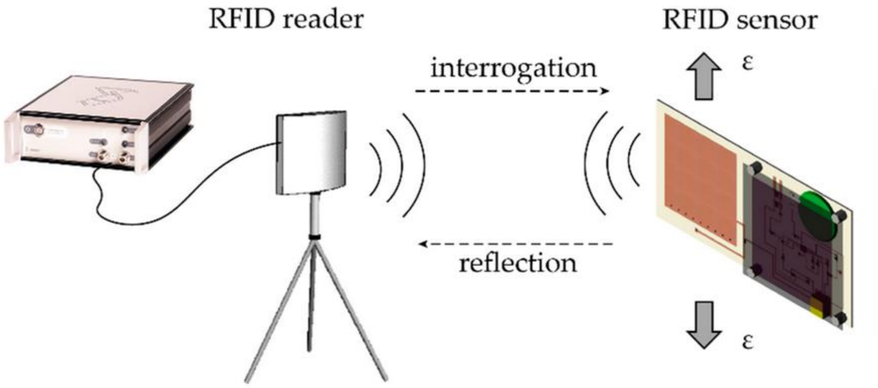


Figure C.5. Sensor-reader set-up

The sensor can be attached to the surface of the intented structural element, here in one of the tests a I-type steel section is selected, and can wirelessly detect crack as well as measure strain. The sensing mechanism is based in the change of electromagnetic resonance frequency. This can be also seen in the resonance frequency formula (1) below, when there is a deformation ε then the L becomes L(1+ε) and a Δf is detected. Hence when there is a deformation of the steel element then the attached sensor also deforms, the resonance frequency changes and the deformation can be measured.

$$f_R = \frac{c}{4L\sqrt{\beta_r(T)}} \quad \text{c, } \beta_R\text{: constant , L: length of the sensor} \qquad (1)$$

- Corrosion and coating lift-off on steel pipe case study by Zarifi et al. (2017)

Zarifi et al. expiriment with a RFID sensor attached to a steel pipe in order to predict corrosion. The mechanism of the sensor is based as the previous examples in resonance frequence change. The sensor (Figure C.6 & C.7) contains a capacitor that when for example water ingresses there is a resonance frequency variation that signifies a change on the system and measures the corrosion.

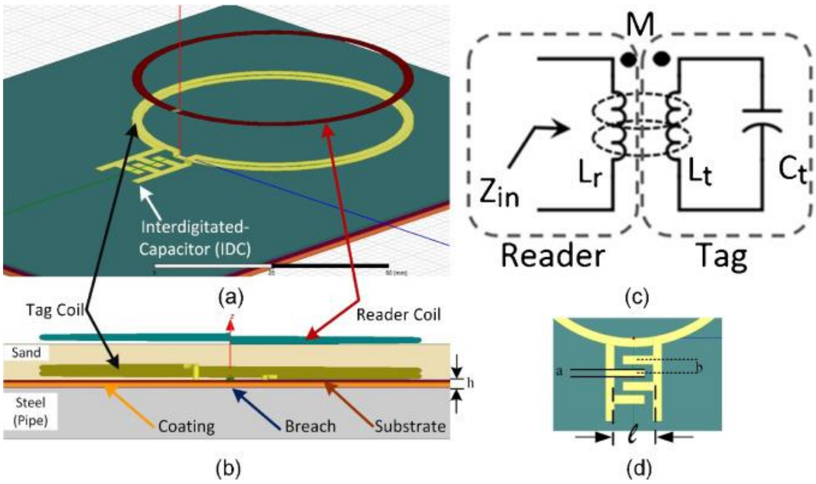


Figure C.6. RFID sensor for measuring corrosion

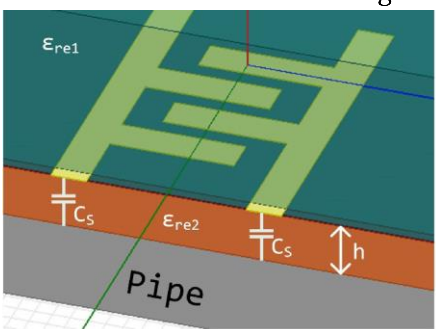


Figure C.7. Closer look on the sensors capacitor

# APPENDIX B: DECISION TREES

Researches have created several decision trees in order to access if a blockchain database is required as well as what type of blockchain should be employed. In the following figures the path that suits better to the present study has been marked with different color.

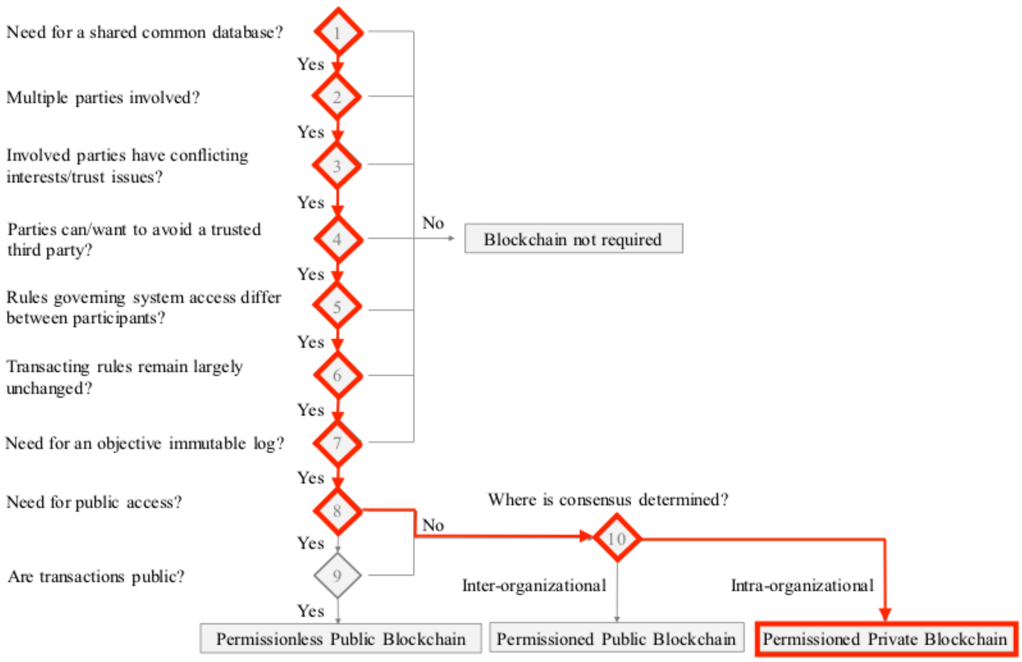


Figure A.1 Pedersen (2019)

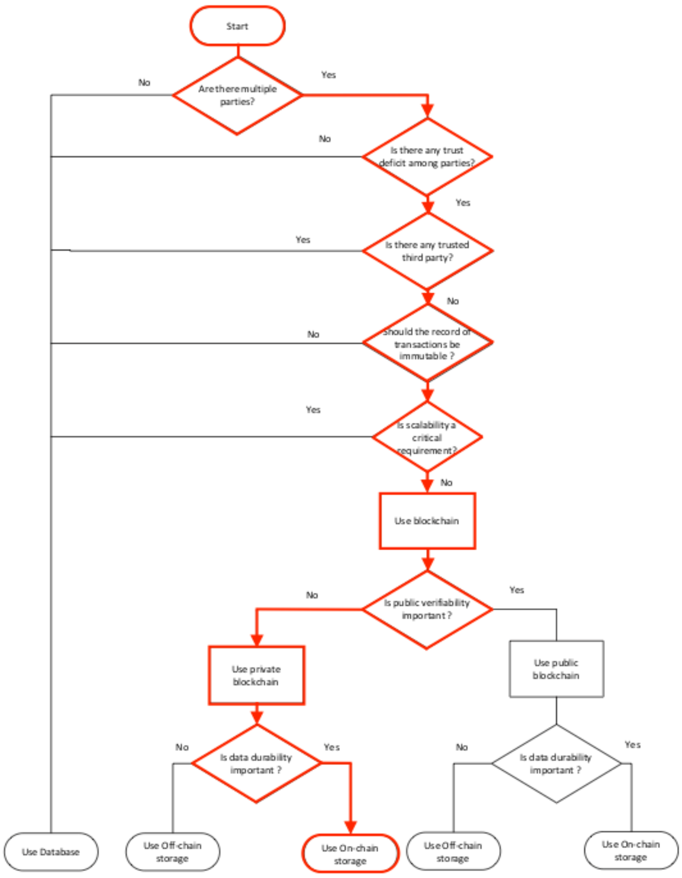


Figure A.2. Chowdhury (2018)

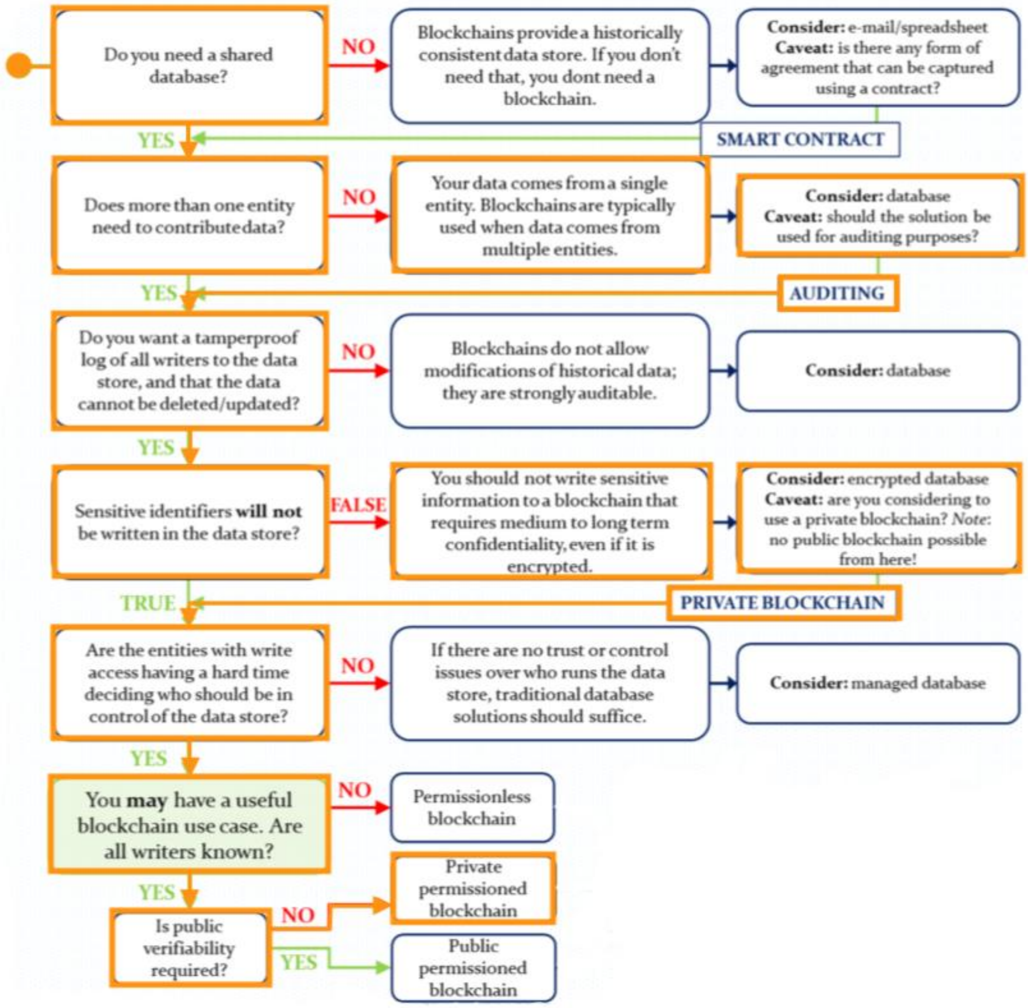


Figure A.3. Seuren (2018)

# APPENDIX C: INTERVIEW QUESTIONS TO EXPERT

Questions

**BIM**

- Is your company acquainted with BIM softwares for projects with steel elements?
  - If not, is it in your plans?
  - If not, what is the reason?
- Do you think that BIM can be used for registering characteristic attributes regarding steel elements during the design and assembly phase?
- Do you find the proposed attributes, during the design and assembly phase, sufficient for the purpose of reuse?
  - If not, what other attributes should be considered?

  **[Reminder of the proposed attributes: the grade of steel, the type of steel (cross-section, section properties), elements Capacity & Loads, type of element's connection, details during the assembly location details]*
- Do you find the proposed attributes, during the *design and assembly phase*, feasible to be registered?
  - If not, what is the main obstacle?
  - If yes, do you register some of the suggested or related attributes during the design and assembly phase?
    - If not, why? Do you find them negligible?
    - Would you consider registering them in a future steel structure project?

**Sensors**

- Do you find it important to keep track of steel elements performance during the *operation and maintenance phase* of a project?
  - If not, why? How would you discover their condition?
- Is your company acquainted with sensors?
  - Have you been acquainted with sensors?
  - If yes, how do they operate them? What data do they register?
  - If not, what are your expectations when you hear about sensors? What might they register
- How do you find sensors as a mean of monitoring steel elements?
  - Would you attach a sensor system in steel elements?
  - Which other way would you suggest?

**Blockchain**

- Do you believe databases which contain information regarding the elements of a building should be more secure, trustworthy and transparent?
- According to literature, blockchain has the potential to be used for bookkeeping in the construction industry. Do you believe such an application could add value in the sector?
  - If no, why not in construction projects while other industries are adopting it.
  - If yes, do you have any prior experience with it? Would you experiment with blockchain?
  - What is your impression from the specific blockchain application?

- What are the strong or weak points that you might recognize in such a system as a whole or individually in BIM, sensors or blockchain application?

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