MSc Thesis Report

Blockchain for Circularity

A Hyperledger Fabric-based Material Passport Framework

Aditya Namburu

5146984

MSc Construction Management and Engineering

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A Hyperledger Fabric-based Material Passport Framework

By

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Preface

In the last few months, the research I have conducted to elevate digital innovation in a circular built environment has been highly enriching. The journey has been very insightful in academic research about the topic and personal and practical experience in conducting research. The thesis has made me confident in handling and delivering well-structured research in the future. The research is not a solo work but a combination of ideologies of various professionals that helped me shape my research better. Thus, I would like to utilise this moment to thank the individuals that played a significant role in the completion of my thesis.

First and foremost, I would like to thank my graduation committee members, my chair Prof.dr.ir. JWF Wamelink, my supervisors, Dr. S.H. van Engelenburg and Dr. DFJ Schraven, for their constant encouragement and support throughout my journey. Research is incomplete if it lacks validation from the professionals in the industry for the proposed ideology. A special thank you to all the interviewees for taking some time off their packed schedule and discussing their honest opinions about the research. It was an excellent opportunity to talk to everyone and share my ideas with them. I gained a lot of insight from their industrial experience.

I would like to extend my gratitude to the Department of Construction Management and Engineering for providing me with an opportunity to explore my research topic with liberal ideologies. I would also like to thank the Delft University of Technology for providing me with facilities to conduct my research with very few hurdles, even during the pandemic.

Last but not least, on a personal level, I would like to thank my family members for their constant support and encouragement throughout my Master's journey. I would also like to thank all my friends for their steady optimistic thoughts that helped me pick myself up after every slump. Overall, the entire journey was highly memorable. I enjoyed writing the report and hope that the person reading this experiences the same.

Aditya Namburu
Delft, 2021

Abstract

The Linear Economy currently follows the Take - Make – Dispose model. This paradigm is based on the consumption of resources rather than the preservation of their value. If this model remains dominant, it will lead to material scarcity, thereby increasing materials prices. The linear economy has a negative effect on nature as this model creates a tremendous amount of waste. Minimising the waste, maximising the value and facilitating the reuse of materials is the foundation of the Circular Economy. Lack of information regarding materials is recognised as one of the primary causes for waste generation. As a result, material passports were created to facilitate information sharing. However, some barriers hinder the application of these material passports. This research analysed the barriers and requirements of material passports and whether these barriers can be addressed through the characteristics of Blockchain technology such as transparency, distributive nature and security. However, a traditional blockchain has its challenges, such as scalability and an unsustainable consensus mechanism. In this research, a conceptual framework of Hyperledger Fabric (Private-permissioned Blockchain) based material passports is developed to tackle these barriers and meet the requirements. The framework developed aims to be helpful to create Hyperledger Fabric-based Material Passport by Material Passport Developers. Additionally, this helps the stakeholders within the built environment to understand the working of Blockchain-based material passports. The framework's validation was carried out by developing two scenarios, i.e., the Blockchain-based material passport and the BIM-based material passport and comparing them. This step was carried out to see whether the proposed Blockchain-based Material Passport framework will address the barriers of BIM-based material passports. In addition, semi-structured interviews with different stakeholders who use material passports to validate the framework.

Summary

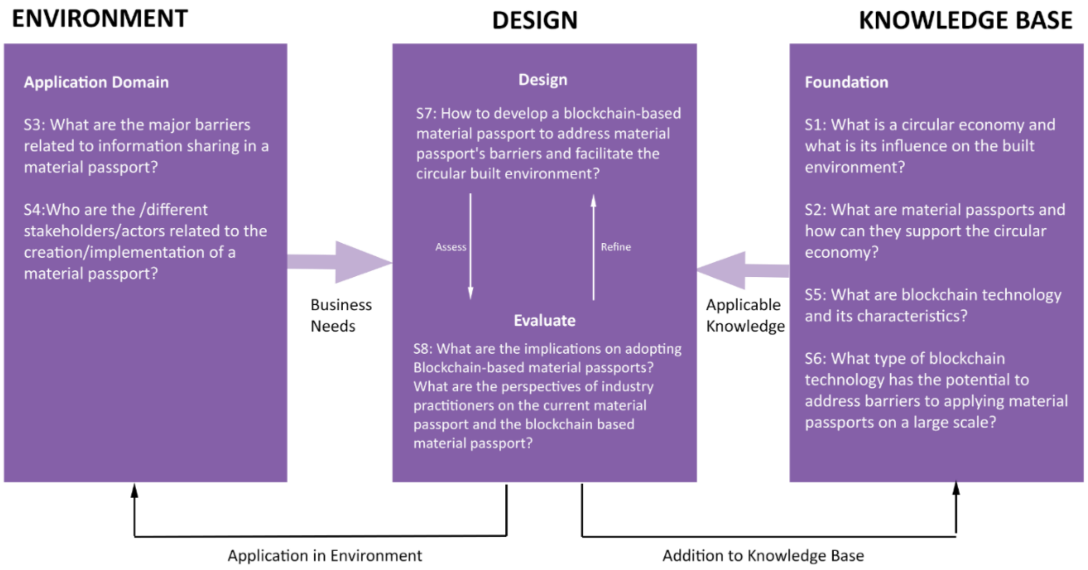
Take-make-dispose is the current Linear economy's model. This paradigm is based on the consumption of resources rather than the preservation of their value. If this model remains dominant, it will lead to material scarcity, thereby increasing materials prices. The linear economy also has a negative impact on the environment as it creates large amounts of waste. To minimise the waste, maximise the value and facilitate the reuse of materials is what the concept of Circular economy is about. Circular Economy is an economic system that prioritises the aspects 'Reduce', Recuse, Recycle and Recovery of materials. Lack of information regarding materials is recognised as one of the primary causes for waste generation. As a result, material passports were created to facilitate information sharing.

Material passports are tools developed to address the barriers of the Circular economy, such as lack of information sharing and materials exchange system. Material passports are intended to track the value of materials throughout their life cycle and introduce the residual value into the secondary market. Material passport will hold the key to this as it will contain information relevant to the different lifecycle stages of the building. A material passport keeps track of the different materials used in the building or components of the building, and how many of them are there. However, some barriers mentioned below hinder the application of these material passports.

Provision of Information	• No incentive for providing the data • Non availability of the data • Some actors do not want to be transparent (Confidentiality issue)
Storage of Information	• Ownership rights on the data
Access to Information	• Every actor cannot have complete access to all the data present on the material passport. It is important to have different access levels to see different data.
Quality of Information	• Managing the quality assurance of the data in the material passports. This raises the question who is responsible for the consequences when the data is not correct. • No standard for a material passport
Presentation of Information	• Lack of uniformity/standard in the data within built environment.

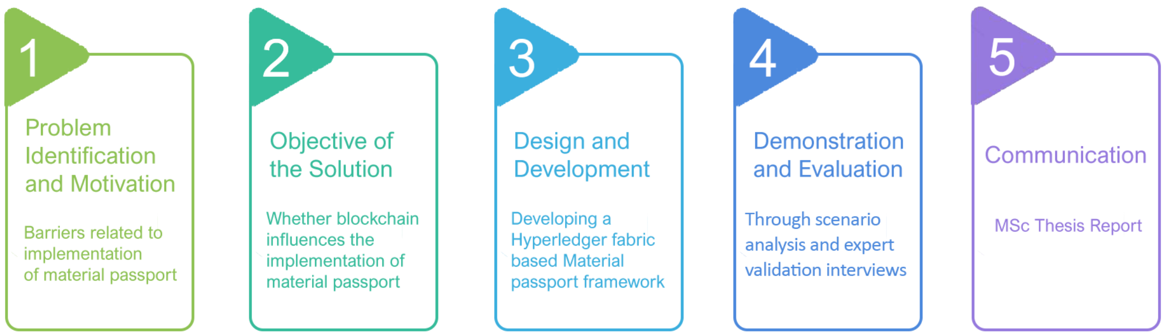
Barriers related to information sharing in material passport

Hence, the main objective of this research is to see whether blockchain influences the application of material passports in the Circular Built Environment. Based on the objective, the main research question has been framed, i.e. '**How can Hyperledger Fabric, a private permissioned Blockchain influence the application of material passports in the Circular built environment?** '. To answer the main research question, several sub-research questions were framed, which are listed in section 1.4. These sub-research questions were linked to the Design Science Research Framework (Henver et al., 2004) to design the research.



Research Design based on DSR framework

The research process is carried out based on Design Science Research Process (DSRP) for Design Science in Information Systems (Peffers et al., 2006). This process includes six steps: Problem identification and motivation, the objective of solution, design and development, demonstration and evaluation and communication, which are elaborated in section 1.6.



Design science research process (DSPR)

This research analysed the barriers and requirements of material passports, which can be addressed through Blockchain technology. In essence, blockchain is a data structure - a kind of database - to which only digitally signed transactions can be added collectively by the peer-to-peer network (without a central party). However, this data must conform to certain conditions (rules), which are also verified collectively. These transactions are grouped into blocks that are added collectively by the network to the back of the blockchain. The last block, therefore, contains the most recently processed transactions. So the blockchain has all processed transactions, from the very first to the very last. All the participants in the blockchain network own a local copy of the blockchain, which they keep up-to-date. We call them nodes. So everyone has the same version of the blockchain. This allows the technology to exchange data and guarantees that everyone has the same and most up-to-date information. Each block contains a timestamp that the network has collectively validated.

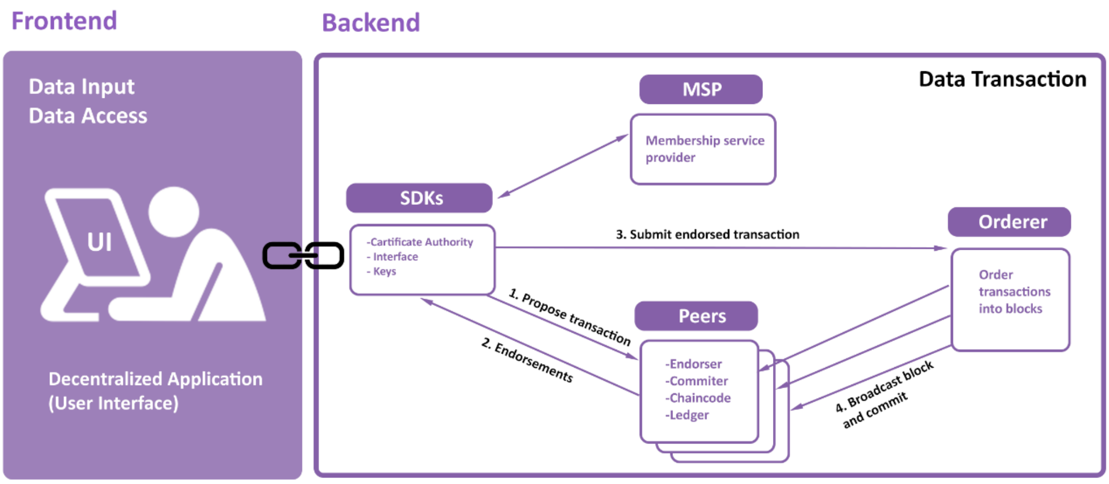
We, therefore, know exactly when a transaction was recorded in the blockchain. Blockchain makes intensive use of cryptography for encryption.

Blockchain technology provides opportunities to enhance the application of material passports based on key features such as its distributive nature, transparency and traceability, immutability and security. However, there are several challenges that this novel technology has to overcome, namely, privacy and security issues, scalability, unsustainable consensus mechanism (computing power) and lack of governance. These challenges hinder the application of blockchain in a business case (Davies, 2020). According to Davies (2020), a blockchain expert, has specific requirements from a blockchain network from a business point of view:

- The consortium creating the network requires a blockchain that allows them to govern who enters the network and the ability to confirm a new user's identity.
- Swift transactions and scalability is a requirement for enterprises.
- The consortium must pre-define the access control list for the exchange of sensitive data.
- A resilient network

Davies (2020) believes that Hyperledger Fabric addresses the issues of a traditional blockchain and meets the enterprise requirements. Hyperledger Fabric (HLF) is an open-source private blockchain-based platform developed by the Linux Foundation. The Hyperledger encourages a collaborative approach to develop blockchain technologies via community process. HLF's architecture aims at the several challenging aspects of blockchain, such as scalability, flexibility, resilience and confidentiality.

For the material passport, a high-level open-source architecture using Hyperledger fabric has been proposed in this study to ensure security, privacy and confidentiality among the stakeholders. The membership service component of Hyperledger Fabric provides a notion of identity management to authorise and authenticate the entities of material passports. It generates and issues digital certificates that specify unique identifiers and details of the users' access privileges. The user employs these certificates to sign the transactions and access the blockchain resources. The digitally signed transactions help verify the stakeholders' legitimacy and access privileges on the blockchain ledger. To architect HLF, members belonging to different stakeholders such as suppliers, contractors, clients, designers etc., are made as endorsers, committers and orderers to ensure trustful, secure and smooth business operations



Hyperledger fabric-based material passport framework

The Hyperledger fabric-based material passport framework was developed mainly to address the barriers of material passports w.r.t to provision, access, storage and quality of information. Since a material passport is more like a shared database with multiple stakeholders providing the data, it requires a tamperproof log and predefined access rights for users to protect the confidential data in the material passport; the practitioners from the built environment think Hyperledger Fabric might be a good fit. The proposed Hyperledger fabric-based material passport framework is validated by developing and comparing the two scenarios; Scenario A: BIM-based material passport and Scenario B: Hyperledger fabric-based material passport. The two scenarios were analysed based on the elements of material passport such as provision, storage, access and quality of information. By performing this step, it proved that the Hyperledger fabric-based material passport could address the barriers related to information exchange in a material passport.

No matter how intelligent or innovative the solution is, it has its disadvantages. However, there are some disadvantages in adopting this framework which are:

- Lack of awareness and understanding regarding the technology.
- There are limited use cases and case studies, but none in a built environment. Most of the use cases are either prototypes or pilots. Some of the use cases from practice include IBM's FoodTrust, TradeLens in the shipping industry and Honeywell's new marketplace for selling new and used aerospace products (Case Studies – Hyperledger, 2021)
- An inadequate number of skilled programmers in the construction industry.

In the interviews, the practitioners from the built environment stated that the organisations need to organise their business process around these material passports besides adopting blockchain technology. This would hinder the process of implementing material passports. Also, there is a splint incentive as the passport makers have to invest time and money in the passport, while the passport benefits are more in the long term. On the other hand, the lack of a standard for a material passport is still a crucial barrier to developing a prototype.

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1. Introduction

1.1 Research Context

Currently, the World economy runs on a linear economic model, i.e. Take – Make-Dispose model, which dates back to the industrial revolution (Andrews, 2015). In this current model, raw materials are used to manufacture various goods, then are sold to users; upon usage, they are finally discarded as waste. Globally, the trend towards urbanization is upward and predicted to increase, with the global population in urban areas rising up to 60% by 2025 (UN DESA, 2018). Additionally, the United Nations predicts that the world population will reach around 8.5 billion in 2030 and increase further to 9.7 billion by 2050 and 11.2 billion by 2100 (World Population Prospects, 2019).

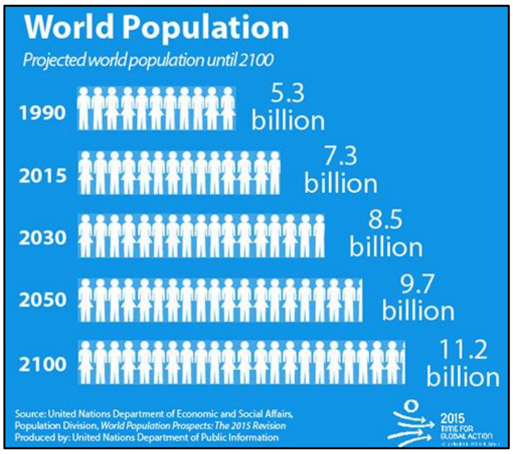

Figure 1: World Population 2100 (World Population, 2019)

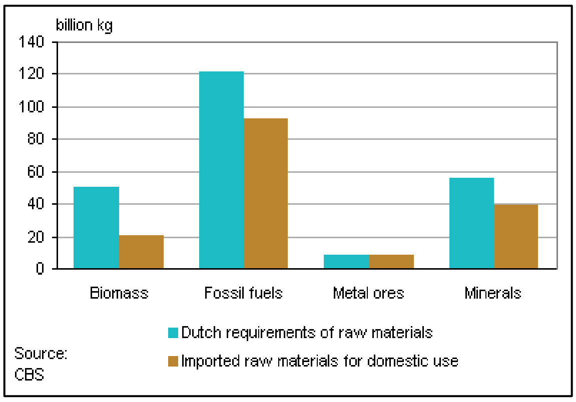

Figure 2: Statistics of Raw materials imported by The Netherlands (Statistics Netherlands, 2012)

As a consequence, Ellen MacArthur Foundation (2013a) identified the following three problems that need to be addressed :

- Increase in demand for raw materials
- Dependency on countries outside the EU
- Contribution towards Climate change

Rapid urbanisation leads to the increased pace of demands for infrastructure and buildings. Adhering to this model will lead to an increased scarcity of raw materials, which will eventually increase the costs and price volatility. These factors will make it very challenging to procure new raw materials (Ellen MacArthur Foundation, 2013a). The scarcity of raw materials will further increase with the increase in the population of the world. This could threaten the supply of natural materials in the future as they are non-renewable and very limited, and many such resources producing these raw materials are already running out of stock (Ellen MacArthur Foundation, 2013; Andrews, 2015). The rising demand for materials can negatively affect the supply security for raw materials, affecting the Dutch economy. The Netherlands imports 68% of the raw materials required for domestic consumption (Centraal Bureau voor de Statistiek, 2012). Globally, the built environment is responsible for consuming 30% of produced energy and 40% of raw materials (Ellen MacArthur Foundation, 2013a).

The current linear economic model not only raises concerns related to the scarcity of materials but also poses a threat to the environment. This is because in the Take - Make - Dispose model, a massive amount of waste is generated. It is a known fact that the construction sector produces a large quantity of waste. The construction sector consumes around 40% of raw materials worldwide while producing 35% of the world's waste (Construction and Demolition debris (C&D)). C&D waste is the waste produced in the process of construction, renovation, or demolition of structures in the form of materials. These structures include – residential, non-residential, and roads and bridges (Nitivattananon, V., & Borongan, G., 2007). Most of this waste is being landfilled or incinerated (Ghisellini, 2016). In the US alone, around 20- 30% of construction and demolition waste is ultimately recycled or reused (Ellen MacArthur Foundation, 2013).

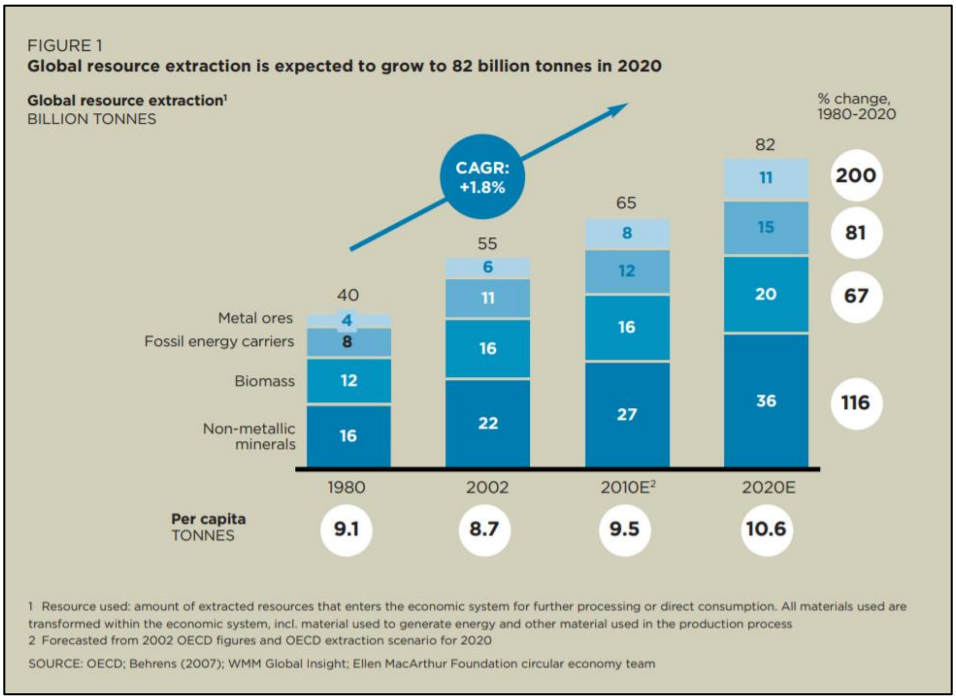

Figure 3: : Construction and Demolition waste (Ellen MacArthur Foundation, 2013)

To address the above-mentioned problems, It is essential to shift from the current linear economic model to the Circular Economic model. A new approach is necessary to restructure and reshape the economy with the concept of circularity. (Prendeville, Cherim, & vii Bocken, 2017). The Circular Economy concept described by Ellen MacArthur Foundation (2015) is as follows:

"The Circular Economy is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles."

Moving to more circular business models would allow Europe to overcome the challenge of material scarcity and climate change (European Commission, 2014a). The Dutch government aims at becoming completely circular by utilising only reusable materials by the year 2050 (Circular Dutch economy by 2050, 2016). They have set an intermediate goal, i.e. a 50% decrease in the use of raw materials by 2030. As stated by the Government of the Netherlands (Government of the Netherlands, 2016, p. 59):

"By 2050, the construction industry will be organised in such a way, with respect to the design, development, operation, management, and disassembly of buildings, as to ensure the sustainable construction, use, reuse, maintenance, and dismantling of these objects. Sustainable materials will be used in the construction process, and designs will be geared to the dynamic wishes of the users. The aim is for the built-up environment to be energy-neutral by 2050, in keeping with the European agreements. Buildings will utilise eco system services wherever possible (natural capital, such as the water storage capacity of the sub-soil)."

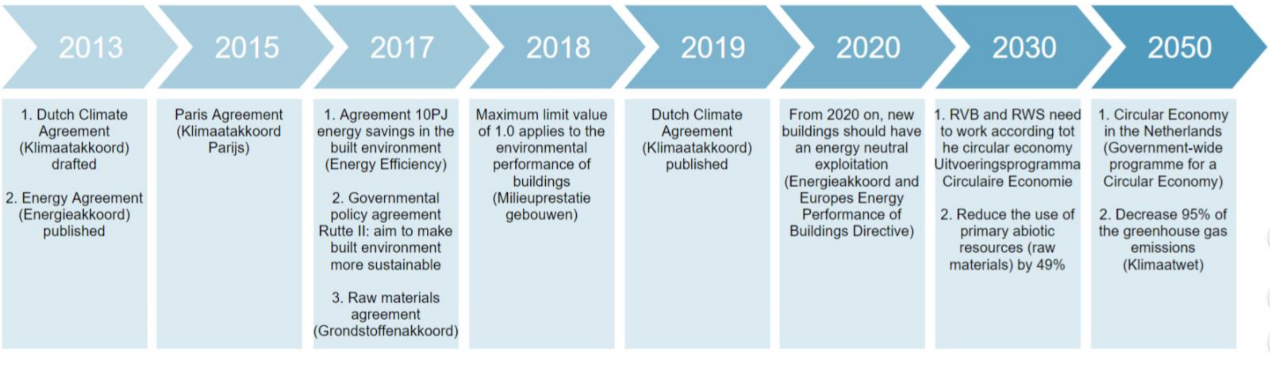

Figure 4: Timeline of measures taken by the central government to ensure the transition to circular economy (Versteeg Conlledo. A, 2019, p. 14)

The Material Passport's introduction is considered a concrete step as it stimulates the materials' reuse. The material passport increased transparency which is required to develop a circular business case and enable the materials' reallocation (Circle Economic, 2015). A material passport represents the information of all the building materials that are present in a building. The information present in the material passport will enable us to understand the potential circular value of materials, components and systems that are used in the building.

Over the last decade, the exponential growth in digitalisation has had a significant impact on society. This is known as "Industry 4.0", and Blockchain is one such digital technology. Blockchain is a decentralised database to which the data can be appended collectively by the nodes in the peer-to-peer (P2P) network. However, this data must conform to certain conditions (rules), which are also verified collectively. These transactions are grouped into blocks added collectively by the network to the back of the Blockchain. The last block, therefore, contains the most recently processed transactions. So the Blockchain has all processed transactions, from the very first to the very last. As the number of transactions grows, so does the Blockchain. The longest chain is known as the True chain. The block's header contains the Merkel root hash of the Merkle tree of the transactions in the block to link the header to the block's body. The header also includes the hash of the previous block's header to link the blocks in a chain. For example, let us take there are six blocks in a blockchain. If the transaction data in Block 2 is modified, then the hash in the header will also be changed. This makes the hash of the header of Block 2 present in the Block 3 header invalid. Therefore the new hash of Block 3 has to be computed via mining which requires a lot of computational power. Similarly, the new hashes of Block 4,5 and 6 also have to be found via mining. To do so requires massive computing power, which makes tampering nearly impossible (Zhang et al., 2019). Many participants in the blockchain network own a local copy of the Blockchain, which they keep up-to-date. We call them nodes. So everyone has the same version of the Blockchain. This allows the technology to exchange data and guarantees that everyone has the same and most up-to-date information. Each block contains a timestamp that the network has collectively validated. We, therefore, know exactly when a transaction was recorded in the Blockchain. Blockchain makes intensive use of cryptography for encryption (Goossens et al., 2020).

Blockchain technology could enable the application of circular economy principles in the built environment, create a market for secondary materials, establish a transparent circular supply chain by sharing information related to materials' origin and their carbon footprints through material passports (Rudolphi, 2018). Through Blockchain, this data can be made available to the various stakeholders participating in the network by maintaining data integrity. Further, the materials and products can be tracked for provenance. The Blockchain's characteristics could revolutionise the construction supply chain, IP (intellectual property) management and regulatory oversight (Bauman, Lindblom & Olsson, 2016). However, there are several challenges that this novel technology has to overcome, namely, privacy and security issues, scalability, unsustainable consensus mechanism (computing power) and lack of governance. These challenges hinder the application of Blockchain in a business case (Davies, 2020). It is believed that Hyperledger Fabric, a private permissioned blockchain, addresses the challenges posed by a traditional blockchain (Davies, 2020).

1.2 Problem Identification

Ellen MacArthur Foundation (2015) suggests creating a material backbone to facilitate the transition towards a Circular Economy. According to their report (Ellen MacArthur Foundation, 2015), a material backbone is a system that can optimise the material circulation and reduce the demand for raw materials. Material passport is such a system designed to address the barriers of the Circular economy, such as lack of information sharing and materials exchange system. A material passport represents the information of all the building materials that are present in a building. The information present in the material passport will enable us to understand the potential circular value of materials, components, and systems used in the building. Material passports are intended to track the value of materials throughout their life cycle and introduce the residual value into the secondary market (Carra & Magdani,2017; Debacker & Manshoven, 2016).

Even though the material passports track the value of materials, provide the circular value of materials and introduce the residual value into the secondary markets, several barriers hinder the application of material passports in the Built environment. Material passports will hold a huge amount of data that needs to be organised and structured properly. Due to abundant data generated by the Architecture, Engineering and Construction (AEC) industry, consistent information exchange systems don't exist, which is a significant barrier in circular initiatives. In their research, Debacker and Manshoven (2016) stated that sharing the materials' intellectual property and product data is still a significant barrier to the successful implementation of material passports. Damen (2012) also states that confidentiality and trust are considered critical aspects of these such information exchange systems as they can break or build make the system (Damen, 2012). Thus, there is a need for a method or process to develop material passports in the built environment to overcome the current barriers. However, there are very limited attempts to overcome the barriers of material passports by utilising other technologies from different domains.

1.3 Knowledge Gap

Based on the problem identified, the knowledge gap for the research consists of two parts. Firstly, the exploration of the application of blockchain technology for Circular built environments, especially for Material Passports, is very limited. However, there is no study on developing a material passport based on Hyperledger Fabric to the researcher's knowledge. Secondly, the industry lacks knowledge on how to develop a blockchain-based material passport. Thus, this research attempts to link the development of material passports with blockchain technology through designing a framework that can guide the developers to develop a blockchain-based material passport. Additionally, this helps the stakeholders within the built environment to understand the working of Blockchain-based material passports. By designing this framework, the researcher believes that barriers related to information exchange in material passports identified during problem analysis, such as sharing confidential information related to materials (IP), are addressed.

1.4 Objective and Research Question

The main aim of this study is to investigate whether Blockchain can influence material passports' implementation in the built environment sector. To accomplish this, the objective of this research is divided into three parts.

First, it is essential to investigate the current status of the use of material passports and how the information exchange within material passports occurs in the construction supply chain. Additionally, explore the barriers preventing or hindering the information exchange from material passports in the built environment.

Second, to examine the characteristics, benefits and challenges of Blockchain technology and investigate the existing types of Blockchain.

Third, to design a framework for Blockchain-based Material Passport and evaluate whether new technology (Blockchain) can address the barriers of material passports and influence is application.

The framework designed in this thesis aims to develop a Blockchain-based Material Passport by Material Passport Developers. This framework will also aid the stakeholders (Clients, Designers, Contractors, Urban Miners, etc.) in the built environment to understand the information exchange through the Blockchain-based Material Passport. However, public blockchains have a major scalability issue and other drawbacks that are not desirable for a business case. Hence a particular type of Blockchain- Hyperledger fabric, a private permissioned blockchain will be analysed to see if this can overcome the challenges posed by a Public Blockchain. In order to fulfil the objective of the research, the main research question is formed.

Main Research Question:

How can Hyperledger Fabric, a private permissioned Blockchain, influence the application of material passports in the Circular built environment?

Sub Questions:

S1: What is a circular economy, and what is its influence on the built environment?

This sub-question helps the readers understand the circular built environment in a broader perspective by focusing on the CE concept and its influence within the built environment. Focussing on CE shines a light on how circular economy principles and strategies helps in understanding the need for retaining building material's value while simulating less usage of virgin materials and production of minimal to zero waste. This sub-question is also necessary to understand the need/importance of developing a material passport. The sub-question will be addressed in Chapter 2 through an extensive literature review.

S2: What are material passports, and how can they support the circular economy?

This sub-question further helps to understand the material passport tool in detail by focussing on why such a tool is needed to stimulate CE in the built environment. Thus, this sub-question addresses the concept of material passports, the types of material passports in practice and literature, and their application in the circular built environment. This sub-question will be answered in Chapter 2 through an extensive literature review.

S3: What are the major barriers related to information sharing in a material passport?

As material passport is still not widely applied in the industry, this sub-question helps understand the existing limitation or barriers for developing material passports. This sub-question will be answered in Chapter 2 through an extensive literature review and validated through expert interviews.

S4:Who are the /different stakeholders/actors related to the creation/implementation of a material passport?

The main focus of this sub-question is to identify all the stakeholders whose interest lies in developing a material passport. Through this sub-question, it is possible to determine which actor holds power to bring change to the development of material passports and who is involved in the development process and their roles, responsibilities, and requirements. Lastly, this sub-question plays a crucial role in identifying interviewees for validating the research. This sub-question will also be addressed in Chapter 2.

S5: What are blockchain technology and its characteristics?

Before implementing blockchain technology for developing material passports, it is necessary to understand the technology in detail. Thus, this sub-question will help understand the concept of blockchain technology and its characteristics, features, and mechanism. This will be addressed in Chapter 2 via an extensive literature review.

S6: What type of blockchain technology has the potential to address barriers to applying for material passports on a large scale?

In practice, several types of blockchain exist with different characteristics, which will be addressed in Chapter 2. Also, it is essential to evaluate and select a particular blockchain type whose characteristics will help address the current barriers for implementing material passports. This will be answered in Chapter 3.

S7: How to develop a blockchain-based material passport to address material passport's barriers and facilitate the circular built environment?

From sub-question 6, all the necessary information for developing a Blockchain-based material passport are gathered. A framework to develop a Blockchain-based Material Passport is designed using that information, thus answering sub-question 7. This designed framework is presented in Chapter 3.

S8: What are the implications of adopting Blockchain-based material passports? What are the perspectives of industry practitioners on the current material passport and the blockchain-based material passport?

The last phase of the research is to validate the proposed framework by comparing the Blockchain-based material passport with the BIM-based material passport. The comparison is made by developing scenarios and analysing them. This step was carried out to see whether the proposed Blockchain-based Material Passport framework will address the barriers of BIM-based material passports. In addition, interviews with actors identified while answering sub-question 4 were conducted to obtain expert feedback and opinion on the proposed framework. Based on this, sub-question 8 is answered in Chapter 4 by analysing scenarios and conducting validation interviews.

1.5 Research Design

Design science research (DSR) methodology is adopted to conduct the research. The design science model is a problem-solving paradigm widely accepted in the engineering and science disciplines (Brocke et al.,2020). The design science research model enhances human knowledge by generating design knowledge through solutions that can be utilised by the practitioners to solve industry problems (van Aken, 2005). The main objective of such an approach is to create knowledge on how specific systems should be constructed/designed by human agencies to meet the desired goals. Thus, the design science research approach is in line with the research objective (i.e. to generate knowledge on how a material passport can be developed using blockchain technology to address the current barriers related to information exchange in material passports).

As shown in Figure 5, the design science research framework consists of three elements: Environment, Knowledge Base, and Design (Hevner et al.,2004). The environment refers to the problem space and is composed of actors, organisations, and technologies. It is possible to obtain information such as the current problems, requirements, and goals perceived by stakeholders through the environment. The knowledge base provides foundation such as theories, models and methods for identifying solutions for the research and methodologies such as validation criteria provide guidelines to evaluate the developed solution. Using the knowledge base, it is possible to design theories and artefacts and evaluate the design through a case study, field study, simulation and experiments.

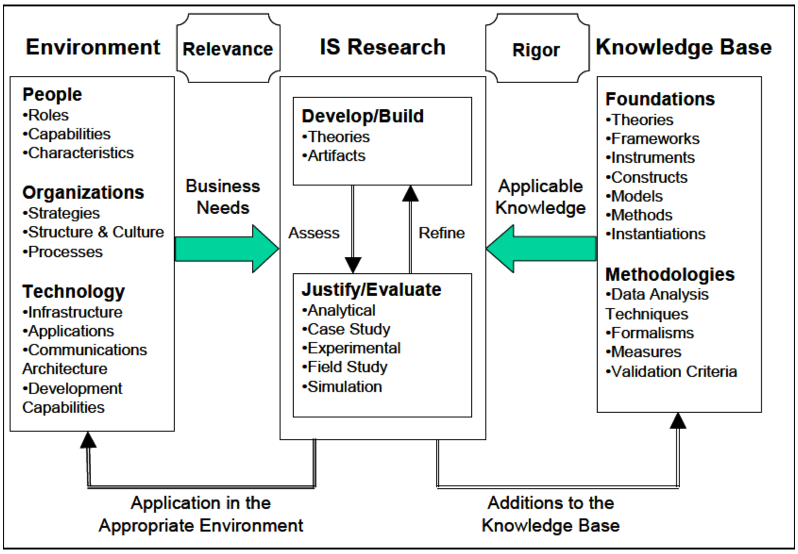

Figure 5 Design Science Research Framework (Henver et al., 2004)

The research is designed by linking the sub-questions framed to answer the main research question with the design science framework, as shown in Figure 6.

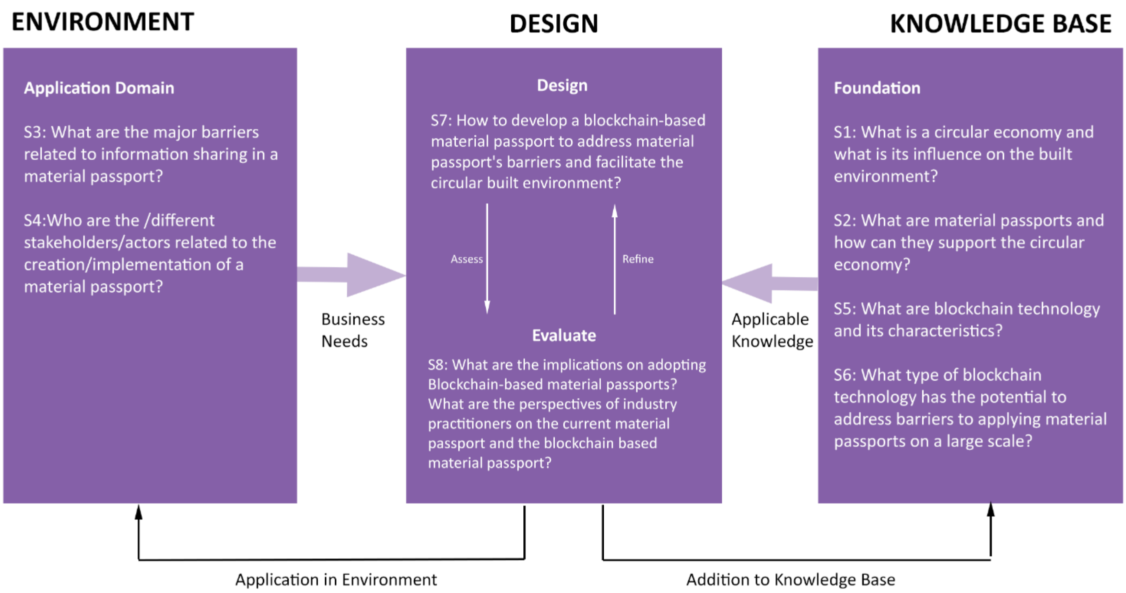

Figure 6 Research Design based on DSR framework

1.6 Research Process

The research design is based on the process, Design Science Research Process (DSPR) for the production and presentation of Design Science (DS) research in Information Systems (IS), developed by Peffers et al. (2006). This process is helpful when conducting and evaluating design science research in information systems. The process includes the following steps: Problem Identification and Motivation, Objective for the solution, design and development, evaluation and communication (Peffers et al., 2006)

a. **Problem Identification and Motivation:** The first step in the research is to identify and define the problem, which is carried out through a literature study and addressed in Chapter 1. Later, to gain in-depth knowledge about the identified problem and concepts related to the problem is understood through extensive literature study, which is addressed in Chapter 2. The main topics of focus through literature study were Circular Economy in the built environment, Material passports and barriers related to material passports and the Concept of Blockchain technology, its characteristics and challenges. This helped in identifying various opportunities on how the technology could influence the implementation of material passports.

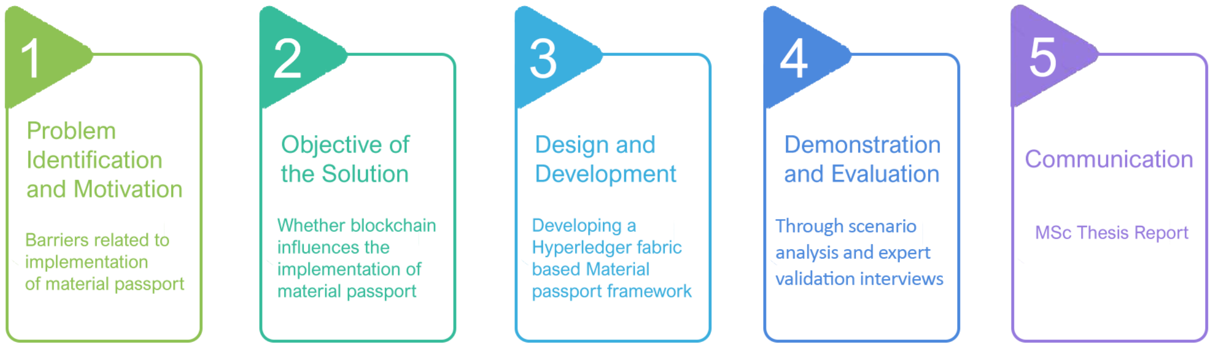

Figure 7: Framework Design science research process (DSRP) (Peffers et al., 2006)

b. **The Objective of a Solution:** The main objective is to see whether blockchain technology can overcome the barriers of material passports and see what influence blockchain technology has on the implementation of material passports. In Chapter 2, the research objective is delt in detail along with the concepts mentioned above.

c. **Design and Development:** To meet the research objectives, an artefactual solution is developed and presented in Chapter 3. It is essential to have theoretical knowledge to design and develop an artefact (Peffers et al., 2006). Therefore, with the insight obtained from the literature study, a conceptual framework for material passports based on Hyperledger fabric (a private permissioned blockchain) was developed.

d. **Demonstration and Evaluation:** In the last step of the research, the framework was compared with the existing scenario, i.e. BIM-based Material Passport, to demonstrate the efficacy of the developed framework and evaluated by conducting validation interviews with experts from the built environment industry. The main aim of conducting these interviews was to validate the barriers related to information sharing in material passports and how the newly developed Hyperledger Fabric-based material passport framework can overcome these barriers and influence the implementation of material passports. The details related to the type of interview, the interviewees and the results are elaborated in Chapter 4.

e. **Communication:** The problem and its significance, the framework, its use and impact/influence on the built environment sector will be communicated to the relevant audience like researchers, professionals in the industry etc., through this MSc Thesis. However, Chapter 5 gives a complete insight (Discussion and Conclusion) on this research.

Figure 8 presents the thesis outline based on the Research Design, Process and the Chapter in which the sub-questions are addressed.

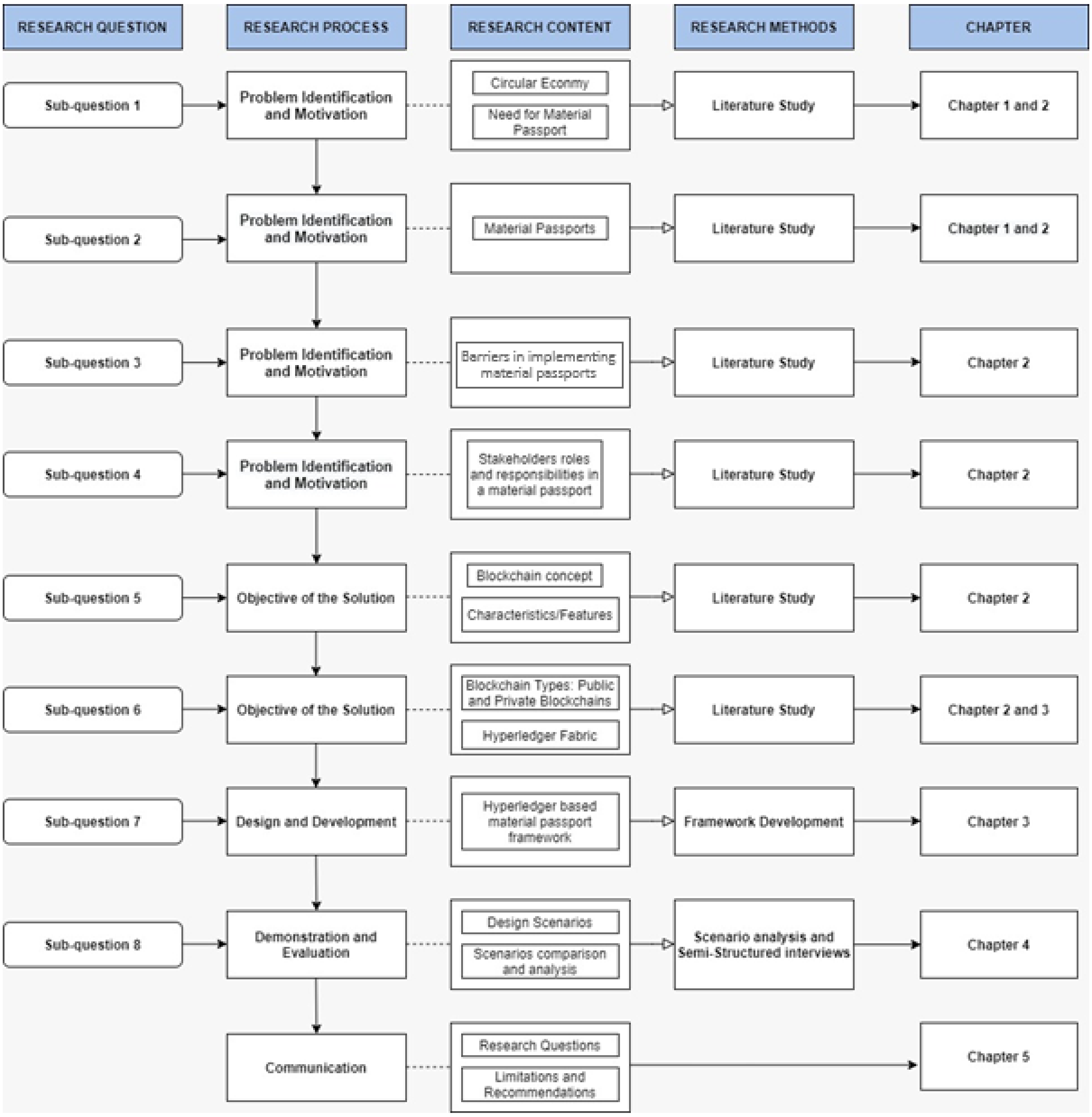

Figure 8 Thesis Outline

2 Literature Review

2.1 Circular Economy

2.1.1 Circular Economy's Definition:

The circular economy concept is gaining momentum among practitioners, researchers, businesses and thought leaders due to the current emphasis on the scarcity of resources in addition to the increasing demand for raw materials, ultimately resulting in high prices of raw materials. The circular economy is a comprehensive and creative approach to a possible future economy, but no clear definition exists. According to Ellen McArthur Foundation, the concept of circular economy is developed from various schools of thought regarding sustainability. They have had all influences in the birth of this concept (Ellen MacArthur Foundation, 2013a).

Table 1: Different Schools-of-thought regarding sustainability (Ellen MacArthur Foundation, 2013a; Rudolphi, 2018)

School of thought	Description
Cradle to cradle (McDonough & Braungart, 2002)	Cradle to cradle is a design philosophy where all the products and processes are a nutritional supply for new products. The philosophy is focused on design for effectiveness in terms of products with a positive impact. This fundamentally differs from the traditional design focus by reducing the negative impacts.
Performance economy (Stahel, 2006)	Performance economy is a philosophy of an economy in loops. The main goals are product-life extension, long-life goods, reconditioning activities, and waste prevention. It also incorporates the importance of selling services instead of products, this idea is referred as the 'service economy'
Biomimicry (Benyus, 1998)	Biomimicry defines her approach that studies the best ideas of nature to imitate these processes and designs to solve human problems. This philosophy relies on three key principles: nature as model, nature as measure and nature as mentor.
Blue economy (Pauli, 2012)	The blue economy is an movement that brings together concrete case studies. It is a combination of ecological, social and economic sustainability. In other words, sustainability that is also good for people and the business case.
The natural step (The Natural Step, 2017)	The natural step uses systems thinking to create a sustainable world where the extraction of raw materials and the creation of unnatural material is minimized. It is also a world where all natural processes, including humans, can fulfil their basic needs.

According to Kirchherr et al. (2017), different definitions are being used to describe Circular Economy. Kirchherr et al. have gathered nearly 114 circular economy definitions to increase clarity about existing perceptions of a circular economy. The findings show that Circular Economy is a system that prioritises the aspects 'Reduce', Recuse, Recycle and Recovery of materials. All these definitions mainly focus on economic and environmental values, but social values are barely mentioned. However, this does not rule out the inclusion of social values in a circular economy, as several other studies demonstrate the social value of a circular economy. (Ellen MacArthur Foundation, 2015; Green Alliance, 2015)

The Circular Economy's definition by Ellen McArthur Foundation is extensively used and also the most employed definition. (Kirchherr et al., 2017). Hence, this report uses Ellen McArthur's definition of Circular Economy, which is as follows:

"The Circular Economy is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles." (Ellen MacArthur Foundation, 2015, p. 5)

Based on this definition, the CB'23 platform developed the Dutch circular construction definition and a circular structure collaborating with various stakeholders. (Ellen MacArthur Foundation, 2017; Platform CB'23, 2019)

"Circular construction is the development, use and reuse of buildings, areas and infrastructure, without unnecessarily depleting natural resources, polluting the living environment and affecting ecosystems by using as many renewable raw materials as possible. Building in a way that is economically, socially, culturally and ecologically responsible. Here and there, now and later" (Platform CB'23, 2019)

"A circular structure is a structure that: as been designed and implemented in accordance with circular design principles and has been realized with circular products, elements and materials" (Platform CB'23, 2019)

2.1.2 Circular Economy Principles

The Ellen McArthur Foundation (2015b) have identified various principles of Circular Economy. These principles help in explaining the concept of the circular economy more comprehensively and are as follows:

1) **Design out waste**: Waste is not generated because materials and goods are built to be reused several times with low energy consumption and high-quality retention. The technical materials can be recovered, refurbished and reused, whereas bio-materials can be processed and returned to the soil.

2) **Build resilience through diversity**: The aspects that need to be prioritised in this dynamic world are versatility, adaptivity and modularity. Due to these changing conditions, the products need to be built in a resilient way.

3**) Relying on renewable energy**: The whole system should be powered by energy from renewable resources. The circularity should begin with looking into the type of energy involved in the production process. The materials' recovery and remanufacturing are based on the availability of physical energy from labour and renewable resources (Joustra, de Jong & Engelaer, 2013).

4**) Think in systems**: It is essential to understand how different parts are influenced by one another in a whole system, and the link between the system and its components is crucial with respect to place and time. The properties of the system are lost when the parts are taken apart.

5) **Waste is food:** Creating value by cascading the products and materials into other applications, i.e. by re-introducing them into the biosphere via non-toxic loops.

These five principles give an outline to the concept of Circular Economy. The fundamental goal of the Circular Economy is to add value to social, environmental, and economic dimensions so that it reduces raw material demand and uses renewable energy sources to reduce its carbon footprint.

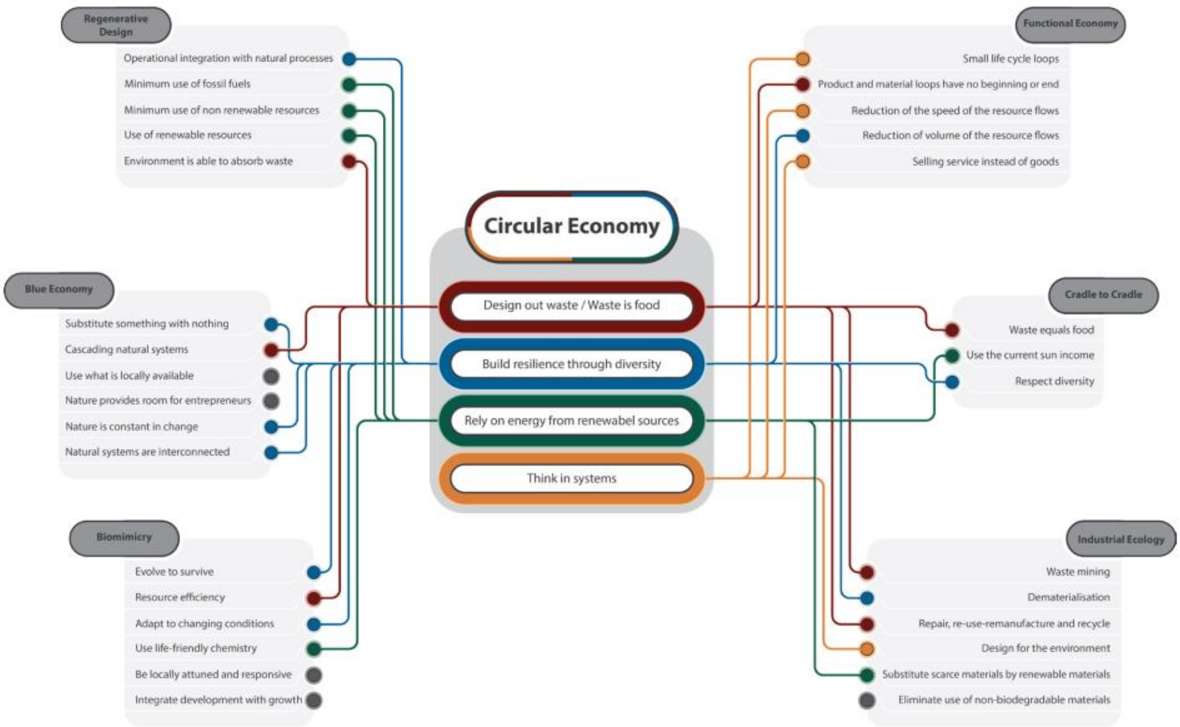

Figure 9: Related schools of thought (Djoegan & Reek, Supply Yourself, 2016)

2.1.3 Circular Economy Models

Different models have been developed to describe the circular economy over the last decade. Some well-known models are the Butterfly Model, widely used R-Model and the new holistic Doughnut Economics of Raworth (2017). These models are described in the paragraphs below.

2.1.3.1 The Doughnut

Kate Raworth (2017) introduced a new economic model called Doughnut Model. This could be the solution to the challenges that the 21st century is facing. The model considers social and planetary boundaries in the form of an ecological ceiling and social foundation. The social foundation is based on the minimum social standards agreed upon internationally and are derived from UN SDGs. The social foundation is to ensure that the people worldwide don't fall short of life essentials. The ecological ceiling is to ensure that humans don't cross the planetary boundaries. Between these two lies the doughnut-shaped space where humanity can thrive along with nature.

Raworth (2017) proposed a doughnut model which focuses on multiple areas of impact for a prosperous environment. This model considers the system beneficial and insightful, and it also represents the circular economy's line of thinking. However, defining the strategies and monitoring their impact isn't straightforward due to these many impact areas. Rosa believes it is more practical to choose models that are developed to achieve circularity. They account for reducing environmental effects by making the best use of materials, electricity, and water.

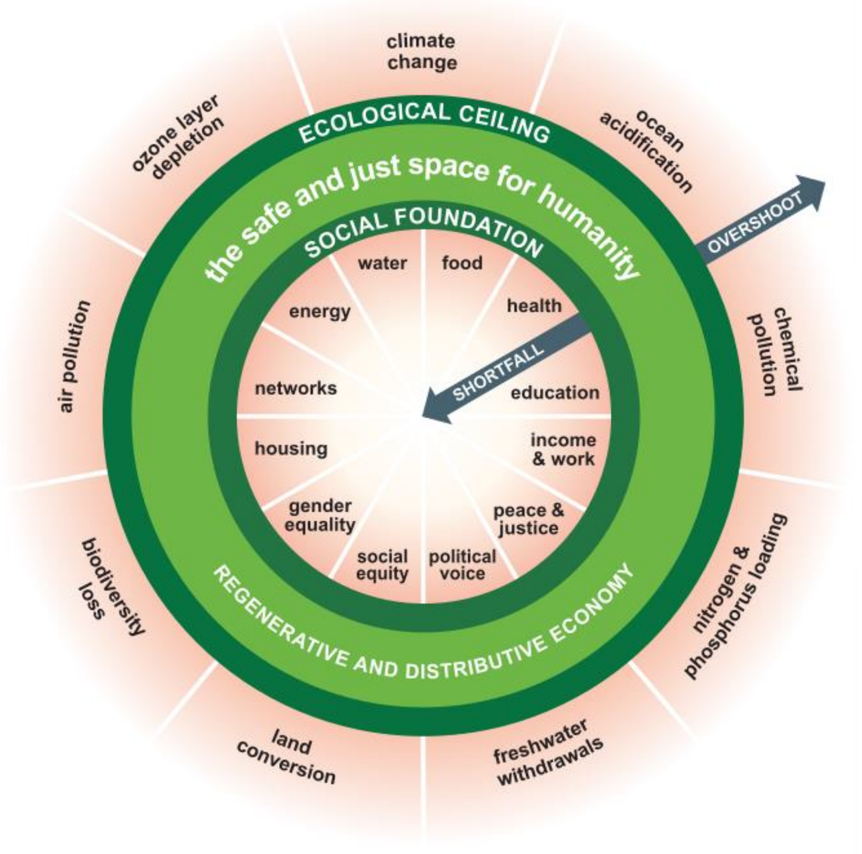

Figure 10: The Doughnut Model (Raworth, 2017)

2.1.3.2 The Butterfly Model

The butterfly model by Ellen MacArthur Foundation is a famous conceptual systems diagram that represents a circular economy. It shows that the material flow is complete and closed in the circular economy. There is zero waste in a fully circular economy as every residue is used to manufacture a new item and ensure that the loop is closed. This system must close the loop and maintain high-quality goods, parts, and raw materials in this system.

In the model, the process along the central vertical axis represents the linear economy, and the loops around them represent possible circular loops and minimise the waste and value leak. There is a distinction between the biological cycle (left) which refers to 'regenerative', and the technical (right) cycle, which refers to 'restorative'. The non-toxic materials are restored into the biosphere (nature) in the natural cycle. In the technical cycle, the materials are restored to the secondary market at their highest quality through refurbishment, maintenance, repair, reuse, remanufacture, and recycling. The model is of a high standard and was created for all products, not just the construction industry.

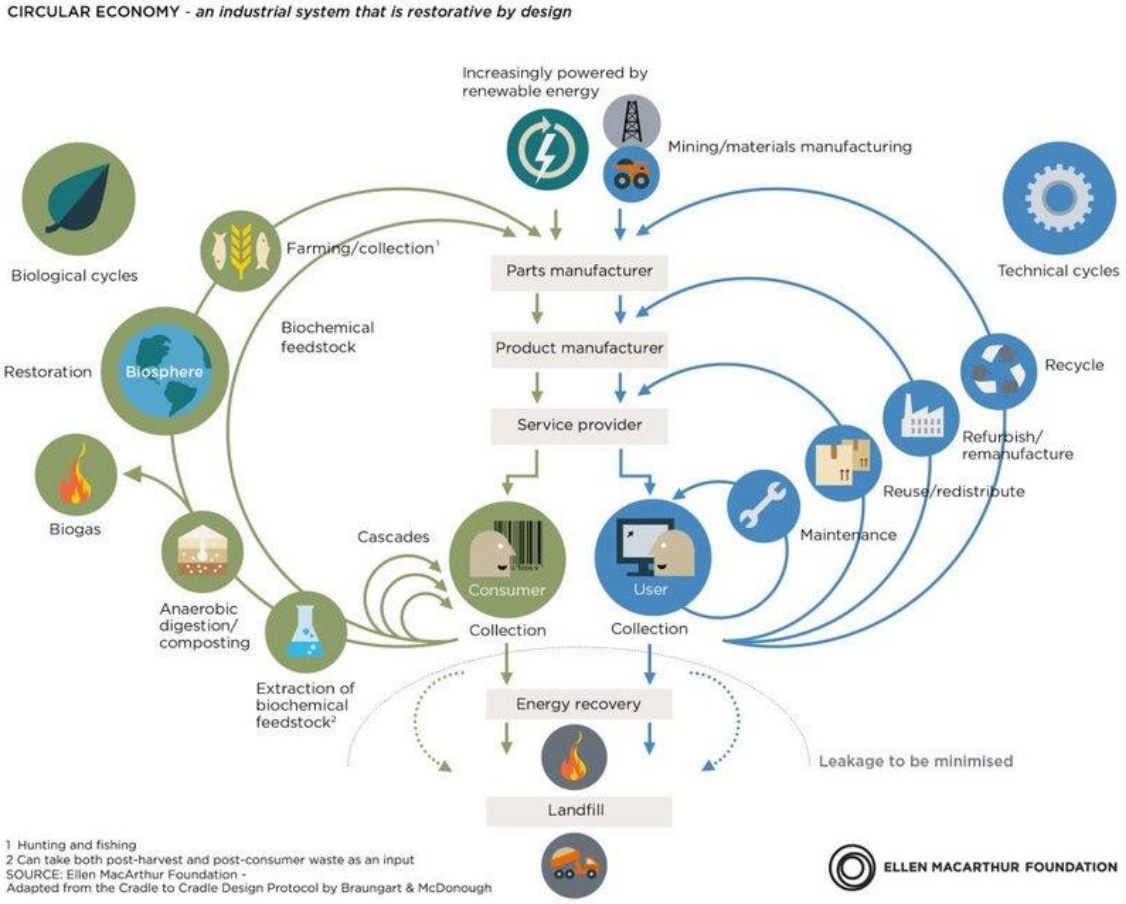

Figure 11: The Butterfly Model (Ellen MacArthur Foundation, 2017)

2.1.3.3 10R Model

The 10R model by Potting (2017) prioritises the circular design approach. R0-R2 is related to narrowing flows, R3-R7 is connected to slowing resource flow, and R8-R9 are related to closing the resource flow. The R model explains the 'How to' of the Circular economy. This model has transformed the conceptual circular model by Ellen McArthur Foundation into circular strategies. These strategies have been prioritised and can be easily understood by practitioners. Potting has divided the 10Rs into three categories which are as follows:

Smarter product use and manufacture: (R0-R2) These are one of the most impactful strategies. The strategies refuse, rethink and reduce are very closely associated with designing. It's about a new way of design thinking that allows demand to be reduced.

Extension of the product's lifespan: The strategies here (R3-R7) focus on retaining products longer that are in use while maintaining, refurbishing or increasing their value.

Useful application of material: This section is related to downcycling and incineration of materials. These strategies have less impact on the system as they are expensive and not so efficient. But, most of the circular strategies are based on these strategies.

Table 2: Circular Strategies- 10R Model (Potting, Hekkert, Worrel, & Hanemaaijer, 2016)

Increasing circularity ↑	Use and produce products more efficient	R0 Refuse	Making a product superfluous by abandoning its function or replace it with another product
		R1 Rethink	Increase product usage by sharing or multifunctional usage
		R2 Reduce	Produce products more efficient by using less (raw) materials
	Increasing the lifespan of products and components	R3 Re-use	Re-use of products that are technical alright by another user
		R4 Repair	Repairing and maintenance increase the lifespan of a broken product
		R5 Refurbish	Refurbish and upgrade old products to increase the lifespan
		R6 Remanufacture	Using components of discarded products to produce new products with the same function
		R7 Repurpose	Using (components of) discarded products to make a new product with a new function
	Efficient use of materials	R8 Recycle	Process materials into materials of the same quality or lower quality (downcycling)
		R9 Recover	Using the energy of burning materials (energy recovery)

2.1.4 Circular Economy in the Built Environment

The cities consist of a massive amount of data, capital, resources and talent. This puts the cities in a unique position to stimulate the transition towards a circular economy. With such resources within such a small geographical area, reverse logistics and material collection can be feasible. This stimulates great chances for circular business models (Ellen McArthur Foundation, 2017a).

According to Ellen McArthur Foundation (2017a), circular cities are self-sustained economies that create a restorative, regenerative, abundant and accessible urban design system. The main aim of circular cities is to produce Zero Waste, maintain the assets' high value, and empower digital technologies. The local value loops are stimulated in circular cities by focusing on the following aspects:

Maker Labs: Encourages locally produced products, distributive manufacturing and repairs.

Collective resource bank: To maintain the material's supply and demand

Information Networks aid in stimulating the exchange of materials and services.

The building industry plays a vital role in the transition towards a Circular economy as it puts a lot of pressure on the environment. Current research tends to focus on macro-level (Cities) and micro-level (material) but not on meso-level (buildings). Pomponi and Moncaster advise that it is critical to research this fundamental level to understand and apply circular economy in a built environment.

When we talk about transitioning towards a circular economy, the built environment is unique compared to the other sectors such as food, supply chain etc. The uniqueness is because of the long lifespans of buildings. Due to this, there might be a change in the form and function of the buildings. (Khasreen, Banfill, & Menzies, 2009) The significant environmental impact by buildings is not during the construction phase but its' operational phase. A considerable amount of waste is generated after the lifetime of the building. One of the efficient ways to counter this challenge of waste generation is by increasing the recycling rate. For the higher recycling rate, information regarding the composition of construction materials is very crucial. The transition towards the Circular Economy will result in significant changes in the construction industry. One such example is the concept of 'buildings as material banks,' which fundamentally alters how material flows must be handled. This concept shines the light on retaining the value of building materials and products at all times by maintaining, refurbishing, repairing and restoring them. This stimulates less usage of virgin materials and minimal waste production (Debacker & Manshoven, 2016).

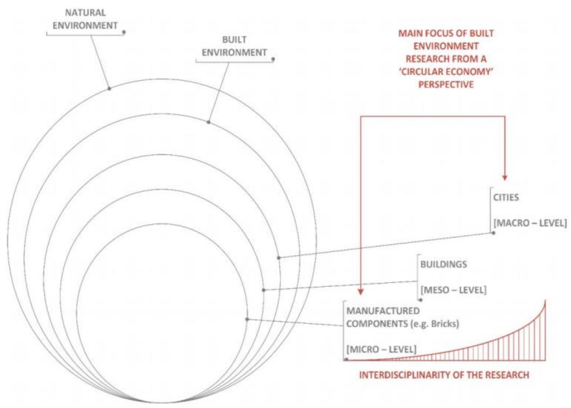

Figure 12: Framing of the built environment (Pomponi & Moncaster, 2017)

2.1.5 Circular Building

Considering the definition of a Circular building, there is unambiguity, just like the definition of the circular economy. The ' Circulaire Bouwen' report puts forward three essential factors for establishing a Circular Built Environment:

- To reduce the negative effect on the environment during the entire lifespan of the building.
- Designing the new building with circular principles and materials.
- The supply should be optimised to minimise the vacant buildings, and building/materials should be reused.

The circular design principles proposed by Circle Economy are: Design and build for disassembly with separate layers, standardize dimensions, make buildings flexible, increase the life span of buildings and utilize reused/reusable building components or recycled raw materials. Sante(2017) suggests that all the actors in the construction supply chain must be involved to achieve circular construction. Green Deal Circulaire Bouwen, a collaborative platform with the Dutch Government, institutions, and companies, aim to stimulate circular ideas and principles into buildings. According to GDCB, the Circular building definition is as follows:

"A building that is designed, developed, managed and used according to the circular economy system, a central aspect of the building is a decrease in the use of raw materials and maximizing reuse. The aim is to use as few new raw materials as possible and where products, raw materials and systems are used, keeping them as long as possible (on a high-value level) in the construction chain"(Green Deal Circulaire Gebouwen, 2015, p. 11)

On the contrary, Copper8 and Alba concepts claim that no building can be fully circular since there are no circular alternatives for most materials used in construction. On the other hand, traditional buildings are circular to some degree as the materials/components can be reused even though they aren't built according to circular principles. (Copper8 & Alba Concepts, 2017)

2.1.5.1 Decomposition of a building

According to Beurskens & Bakx (2015), the buildings are dynamic structures that constantly adapt to the environment and users' needs. To understand the circular building, first, it is essential to know the decomposition of a building. A structure can be decomposed into six different layers, each comprising a different lifespan. This is also known as the 'Shearing layers' model developed by Brand (1994)

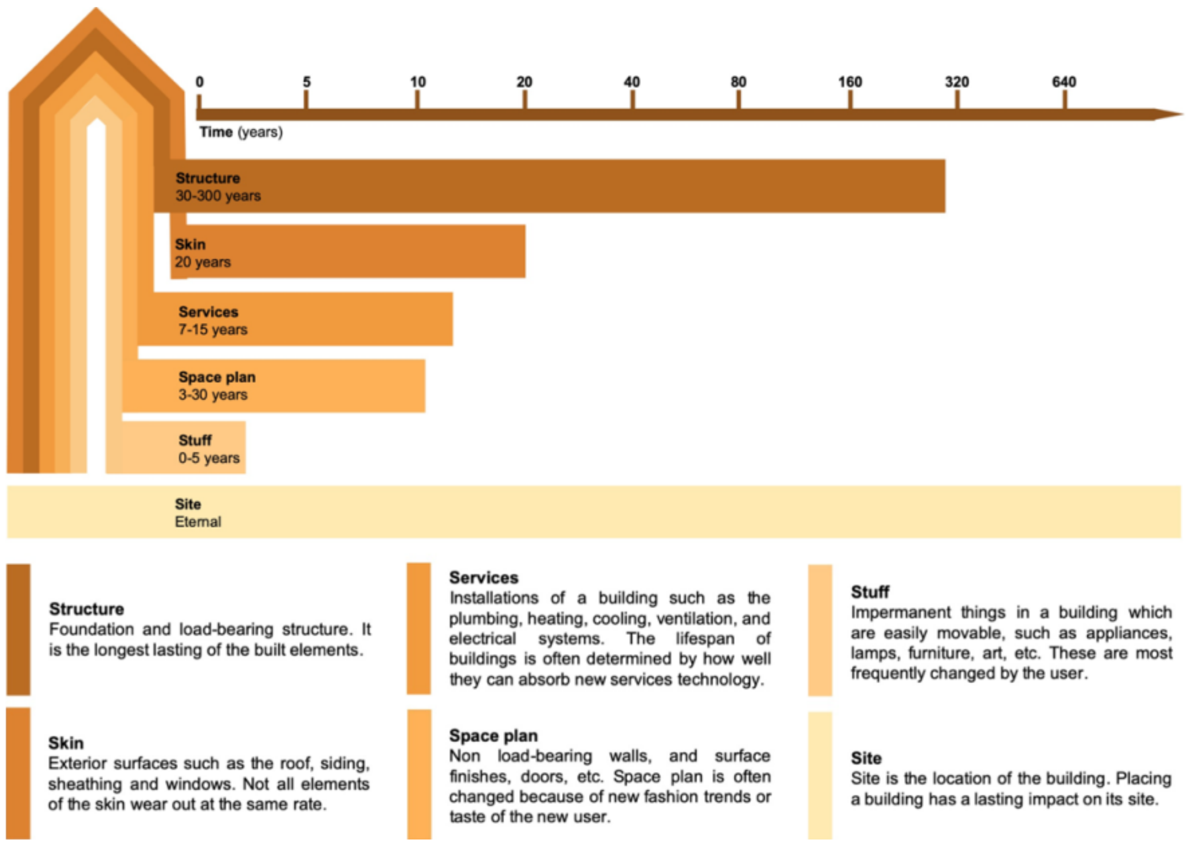

Figure 13: The different layers of building and their life expectancy (Brand, 1994; Crowther, 2001; Rosa, 2020)

A significant role is played by the lifespan of the building in the tension between the changing environment and the building itself. As a result, determining the lifetime of a building or a component of a building is difficult. Every structure has a technical, functional, aesthetic, and financial lifespan which varies in length and cycle.

- Functional lifespan: This is the period between completing a building and the moment it does not meet the desired requirements anymore. (Pijl, 2017)
- Economical lifespan: This is the period between completing a building, and the moment another alternative with lower or at least the exact exploitation costs exists (Pijl, 2017)
- Technical lifespan: This is the period between the completion of a building and the moment it cannot achieve the mandatory technical requirements anymore (Pijl, 2017)
- Aesthetic lifespan: The period where the buildings' requirements are met with respect to the appearance and surrounding environment.

From a technical perspective, a building can be described at multiple levels of abstraction with respect to the hierarchy of material levels. Durmisevic and Brouwer (2002), in their article, have described four levels, i.e. Building, System, Component and Element. Similarly, Copper8 and alba concepts have added another level to this model, which is material level.

Currently, the construction industry follows the linear economic model and is fragmented as well. In order to achieve circularity, the process must be changed (Kubbinga et al.,2017). Debacker and Manshoven have divided the lifecycle of a building into four stages. Namely, Design, build, operate & use and repurpose & demolish and have described them.

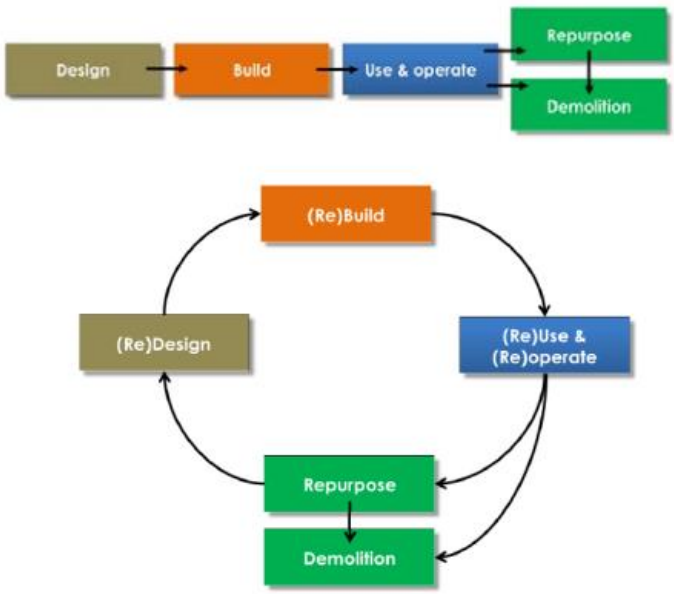

Figure 14: Different Stages in stages of a building (Debacker and Manshoven, 2016)

- Design: In this phase, all the designing, planning and financing of the project is specified.
- Build: In this phase, the project is realized

- Use & Operate: In this phase, the building serves its function as users use it and operate to maintain the users' requirements.
- Repurpose and Demolitions**:** In this phase, the building or its components get new a new purpose. But currently, not many products/materials are being extracted for reuse. Instead, most of the time are being demolished.

2.1.5.2 Stakeholders involved during Lifecycle of a building

Identifying stakeholders is crucial for a circular economy as they possess significant influence over the construction industry and its supply chain, which can modify the system. Mobilizing stakeholders to stimulate a circular economy is possible only by understanding the power and interests of the involved stakeholders. To achieve a circular supply chain, it is crucial that all the actors involved aim towards achieving the best for all parties, minimize waste and value leaks and (re)use materials that keep high value throughout the life cycle. Over time, companies could gain a competitive advantage by building integrated value chains. (Carra & Magdani, 2017)

Table 3: List of Stakeholders and their roles (Carra and Magdani, 2017; Rudolphi 2018)

Actors	Description
Investors	Bankers and other investors may need to switch from traditional buy-sell models towards longer investments terms. Compared to the linear investment models there will be a longer time gap between the acquisition of assets and the revenue that is derived during the investment period. Technology that is able to close the loops may not be developed enough which will further increase potential risks. Construction companies already often ask banks to put material assets on their balance sheets. Investors always have to take into account that possible replacement materials may enter the market (Carra & Magdani, 2017).
Asset holder / Developers	The change towards a circular economy is hard for asset holders and developers as the contract prices related to maintenance and operation of the building are extremely hard to determine. This is even more complex when the longer lifespan of buildings is considered (Carra & Magdani, 2017).
Designers	The role of designers is becoming more relevant within a circular economy. They might become a facilitator that will integrate competences and mutual benefits across the different stakeholders (Carra & Magdani, 2017).
Manufacturers / Suppliers	Manufactures and suppliers need to be more open about their products to increase the transparency in the value chain. In a circular value chain the materials of products need to be known to allow for reuse, recovery and recycling. Material passports may provide the answer for improved transparency. Currently most suppliers are reluctant to reveal data that might reduce their competitive advantage within the market (Carra & Magdani, 2017).

Contractors	The contractor is involved within important decision making and procurement options about the lifecycle of an asset and will have the opportunity to procure circular materials. New technologies such as material passports and data embedded into virtual models are needed to give assurance of the quality and legality of the used materials (Carra & Magdani, 2017). Within the change to more circular business models as per-per-use the focus within the process can change from the contractor towards the suppliers.
End user / Facility managers	The occupiers of commercial buildings are a significant source for waste generation through the use of the building and from the impact of materials used in fit-out, alteration and refurbishment. Circular business models will reduce the quantity of waste streams being produced over the lifetime of a building (Carra & Magdani, 2017).
Recycler / Reuse banks / Demolishers	Demolition contractors and recyclers are getting a different role inside a circular economy, with increasing their focus on becoming disassembly experts to release materials which will be otherwise locked up in buildings (Carra & Magdani, 2017).
Government	The government can be structured within different levels divided from a local level, to a national level, and European level. Every level has its own authorizations. The government can guide the market with regulations (Leising, 2016).

2.1.6 Challenges for circular economy

Ritzén and Ölundh Sandström (2017) have listed several challenges that hinder the transition towards the circular economy. There are many challenges identified, and those are most often connected. This exemplifies the complexities of a circular economy and what is necessary to make the change. Table 4 lists the challenges which are categorised into: financial, structural, operational, attitudinal, and technological. In the report 'Unleashing the power of Circular Economy' by Kok, Wurpel and Ten Wolde (2013), numerous challenges were mentioned, which were categorised into different groups: Financial, Institutional, Infrastructural, societal and technological. However, the categories mentioned aligned with those mentioned in the research by Ritzén and Ölundh Sandström (2017). Winans, Kendall and Deng (2017) believe that lack of exchange of information is a significant barrier for successful Circular Economy initiatives. They also stated that the lack of a material exchange system and information regarding materials prevents the material exchange among the various stakeholders involved in the construction industry.

Table 4: Barriers for moving towards CE (Ritzén and Sandström,2017)

Financial	Measuring financial benefits of circular economy
	Financial profitability
Structural	Missing exchange of information
	Unclear responsibility distribution
Operational	Infrastructure/ Supply chain management
Attitudinal	Perception of sustainability
	Risk aversion
Technological	Product design
	Integration into production processes

2.2 Material Passport

Material passports are tools designed to address the barriers of the Circular economy, such as lack of information sharing and materials exchange system. Material passports are intended to track the value of materials throughout their life cycle and introduce the residual value into the secondary market (Carra & Magdani,2017; Debacker & Manshoven, 2016). To realize the circular potential of material, products or systems, it is crucial to obtain information regarding the tasks performed in every phase of the lifecycle of the building. Luscuere (2017) proposes that a material passport will hold the key to this as it will contain information relevant to the different lifecycle stages of the building. Over time, many instruments have been developed to facilitate materials and information exchange but are being operated on a smaller scale. It requires trust, increase in cost for coordination for such systems at a smaller lever to evolve (Damen, 2012). Such a system needs quality data management and high-quality data input regarding properties of materials, composition, reusability of products and many more. Unfortunately, no system in the market promotes this. According to Geldermans (2016), Building Information Modeling (BIM) is frequently mentioned as a potential solution. During the initial design stages, the BIM-based material passport acts as an optimization tool. At the end of the lifecycle of a building, it is more like an inventory for a secondary raw material cadaster (Honic et al., 2019). Nagel and Korbee (2017) have shown a data gap in the Take-Make-Dispose process without a material passport. This can be addressed by implementing material passports as the information they hold is the key to the reuse loop of products and materials (Nagel and Korbee, 2017).

Material Passport can facilitate the documentation of qualitative and quantitative data of building materials and components that are essential for Circular Economy (Honic et al., 2019). The material passports have a great potential to keep the value of materials at the highest level (Luscuere, 2017). The data that material passports contain can be made readily available for impact assessments (Honic et al., 2019). There are several uses of material passports listed in the report 'Materials Passports- Best Practice' (BAMB,2020). The report mentions that the use of material passports can enable circular product design, facilitate material recovery and reverse logistics, assist the stakeholders in decision making for choosing circular and sustainable projects, products and materials. The main aim of material passports is to minimize ecological footprint by eliminating waste and reducing the use of raw virgin materials. The use of material passports from the perspective of experts in the built environment sector has been discussed in Chapter 4.

2.2.1 Definition

A material passport is a tool that tracks the different materials used in the building or components of the building and how many of them are there. This information is recorded and transferred to different actors involved in other lifecycle stages of the building, such as suppliers, contractors, demolishers etc. The article ' De cirkel is rond- De circulaire toekomst van Nederland' by ABN Amro bank describes material passport as:

" A materials passport describes all the materials, components and elements used in a building. It is a digital model, a database, that identifies which materials are used in the building components, where they are located in the building, how to dismantle them, who owns them, what is the quality when they become available for reuse. In this way, value can be assigned to these materials for reuse, resale and/or recycling. The materials passport thus gives materials an identity and a value" (Bokeloh, Krayenhoff, Menkveld, Raes, & Schotsman, 2017, p. 15)

In the research conducted by Damen (2012), she has pointed out specific characteristics that a material passport should possess. They are:

- Relevant information is to be shared by all the actors involved in the construction supply chain.
- Updating the information regularly
- Uniform format
- Information should be easily accessible. At the same time, Material Passport should also address the confidentiality issue.
- Customization of the data within the passport should be possible

2.2.2 Existing and Related passports

In their report, Debacker and Manshoven (2016) have considered thirteen product passport initiatives; see table 5. These passports might not be relevant to the built environment but can help gain insight into how the data can be organized, presented, and shared. A multi-criteria was also performed to analyze the usefulness of the passports.

Table 5: List of existing and related material passports (Debacker and Manshoven, 2016)

Passport name	**Initiator's name**
C-passport	Cirmar
Circularity passports	EPEA
Cradle to Cradle Passport	Sustainable Shipping Initiative
Declaration of Performance (DoP)	EC Product Directives
Environmental Product Declaration (EPD)	ISO
Health Product Declaration (HPD)	Health Product Declaration Consortium
Material Safety Data Sheet (MSDS) & Safety Data Sheets (SDS)	The Hazard Communication Standard, OSHA
Product Passport	European Resource Platform
Raw Materials Passport	Turntoo & Double Effect
Recycling Passport	Agfa-Gevaert & Electrocycling GmbH
Resource Identity Tag or Tool	Groene Zaak/Metabolic/Fairmeter.org
Technical passport for equipment	Kazakhstan & Russia
Workwear Passport	Dutch Awareness

BAMB: Centred on EPEA's circularity passport, BAMB (Buildings as Material Banks) has developed its material passport. They argue that knowledge about components and materials should be readily available to transition to the circular construction industry. This data is essential for efficient recovery and reuse. This material passport ensures that the value of goods, parts and materials is maintained or increased over time. It encourages to choice of sustainable and circular goods and materials (Debacker & Mashoven, 2016).

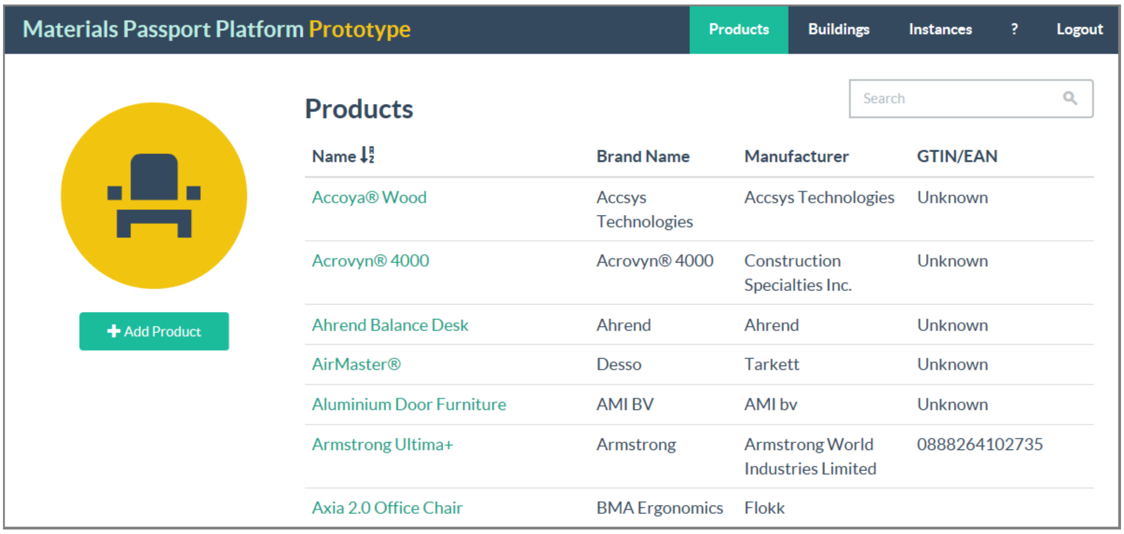

Figure 15: Material Passport Platform Prototype (Materials Passports - BAMB, 2019)

Excess Materials Exchange (EME), a digital product matching platform, has developed its material passport called The Resource passport (Excess Materials Exchange, 2021). They provide a smart matchmaking feature where the clients are matched with potential customers who are interested in high-value reuse. It provides the characteristics of the products and the resources used by these products. The resource passport serves as a data repository for the entire lifecycle of the product. This passport stands out because of its cross-sectoral approach and not just focus on the built environment. However, the resource passports focus on individual products. The use of this platform for complex systems like buildings has not been established yet.

Madaster: One of the widely known companies working on material passports is Madaster. Madaster is a Dutch non-profit organization that developed 'Madaster' platform. The platform's main focus is to document, register, store, and exchange building materials' data. Multiple material passports can be saved on this platform (*Home - Madaster*, 2021).

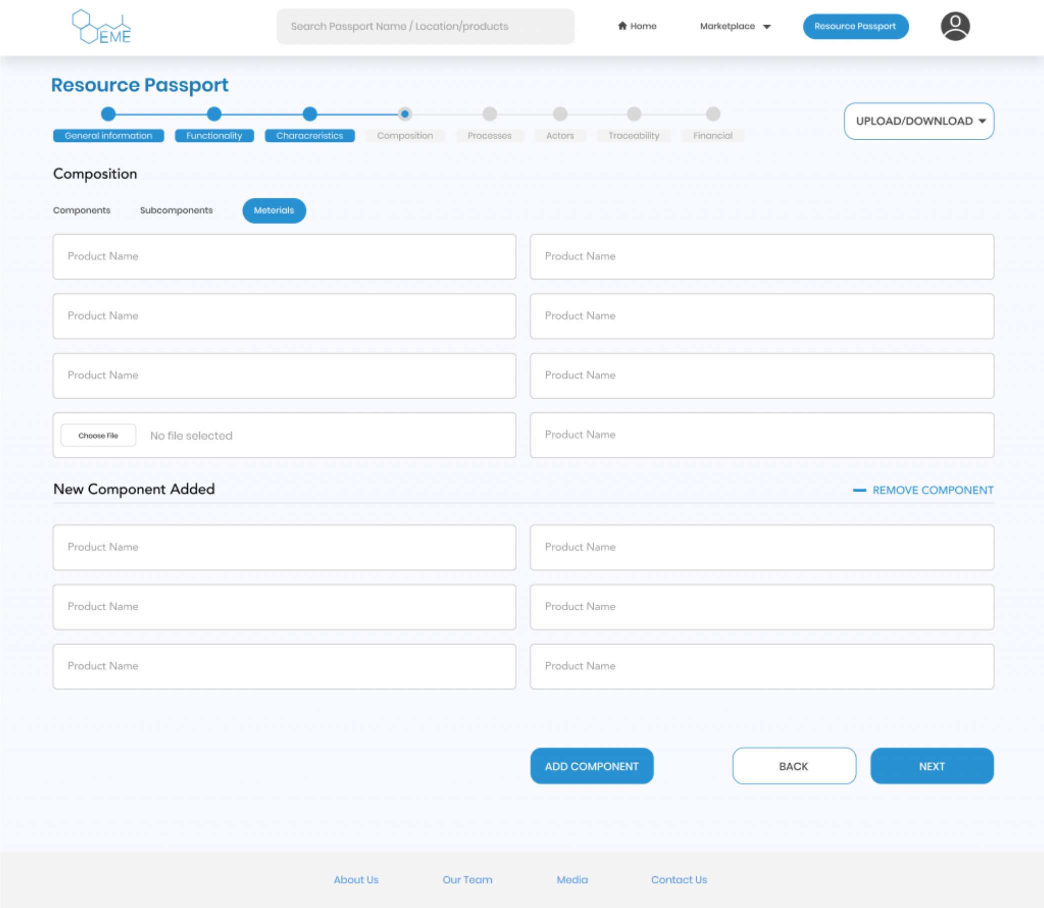

Figure 16: The Resource Passport (Excess Materials Exchange, 2020).

It can automatically generate a material passport when provided with correct data by uploading BIM-file onto the platform. The passport gives insights regarding the different materials used in the building and their corresponding quantity. Madaster adopts the concept of shearing layers developed by Brand (1994) to categorize the building into structure, skin, service, stuff, site etc. Based on Material circularity indicators developed by Ellen McArthur Foundation, Madaster indicated the Circularity Index of each layer (Madaster, 2018). Currently, Madaster is focused on improving the quality and functionality of its material database. However, this Database will have an added value only when it reaches relevant stakeholders. They also mention the need for relevant information access and exchange among the stakeholders. As a result, there is a need to look beyond just developing a material database and investigate other factors essential for shaping a greater ecosystem.

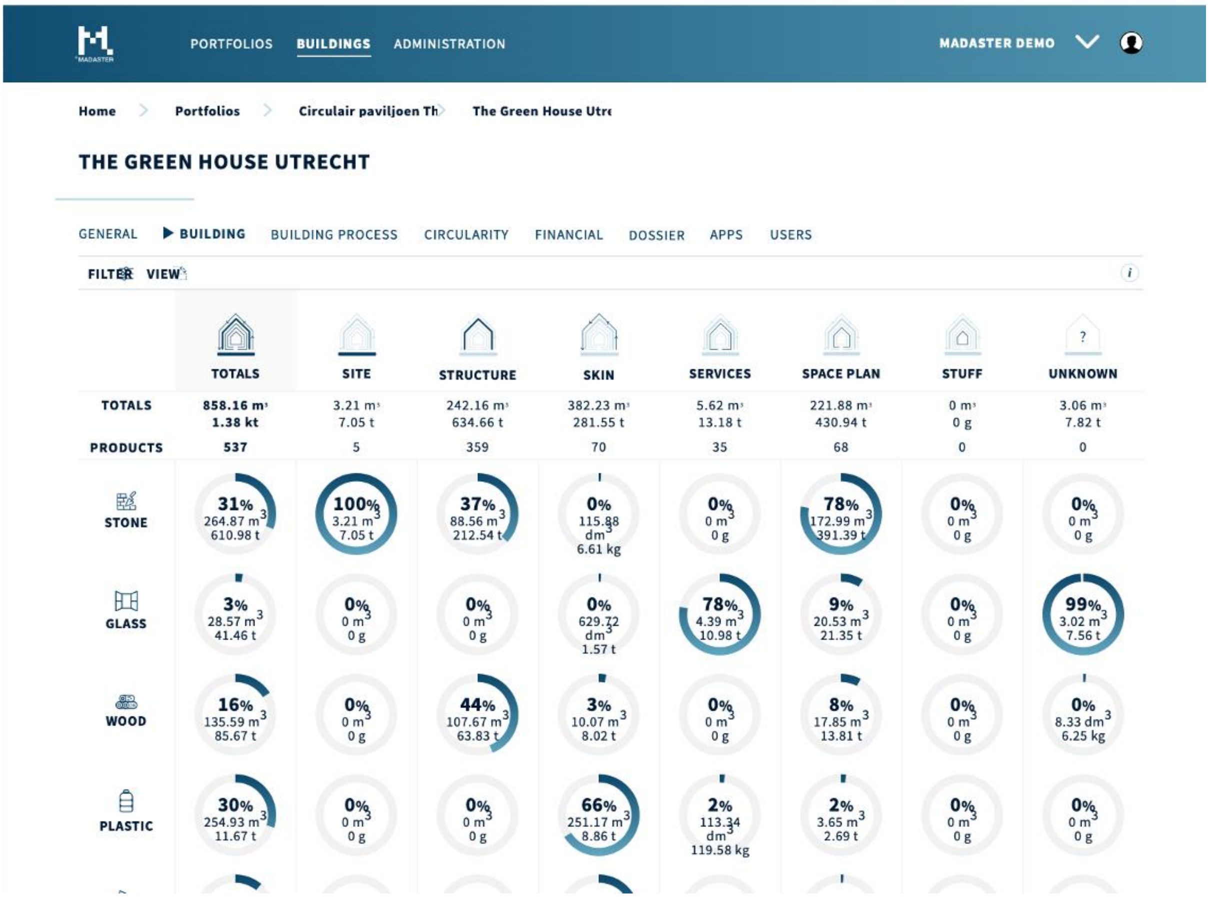

Figure 17: Madaster Platform Demo (Solar Impulse, 2018)

ABN AMRO, along with the architectural firm de Architekten Cie, developed their material passport LLMNT (de Architekten Cie, 2017). In figure 18, the LLMNT passport's contents are provided. This passport is being used as an example of what a material passport contains for this study. The contents of the passport are classified into four categories, namely:

- Potential- Object's potential to retain the value
- Guarantee- The data in this category explains how the matter can be retained
- Revision- The data verifies whether the object has retained the value
- Specifications- Object's specifications such as dimensions, certificates, owner etc.

The icons present beside the contents represent the actors who will be using the data.

The material passport LLMNT adopts the structure developed by Durmisevic and Brouwer (2006). This structure also embraces the concept of 'Shearing layers' corresponding to the decomposition of a building developed by Brand (1994). All of the data is not required at every level. Hence, corresponding data must be assigned to different levels such as System, Element, Component and material level, which is visible in figure 19. The logo under each level refers to the different categories as in figure 18. The number corresponding to the logo represents the data that needs to be recorded as per figure 18. If the number is **Green,** then the data regarding the object is recorded at every level. If Orange, then the information is recorded at the highest level. (If an entry has the same value on several levels, it only needs to be written once at the highest possible level). If the data is **Red,** the data is not required at that level.

no.	Potency	Guarantee	Overhaul	Specifications
1	Circular potential	Instruction manual maintenance	Log maintenance	Performance
2	Disassembly power	Manual management, connections	Log management, connections	Dimensions
3	Date of released	Manual management, Services	Log management, Services	Weight
4	Financial value	Manual management, finishes	Log management, finishes	Coding + name
5		Instruction manual edit	Log assembly, As-built	Supplier
6		Instruction manual disassembly	Log assembly, defects	Certificates
7			Log Demon-tage, flaws	Location
8				Delivery
9				Owner
10				Technical lifespan
11				Superstructure material
12				Cycle material
13				Hazard class material

Figure 18: Content of Material Passport (de Architekten Cie, 2017)

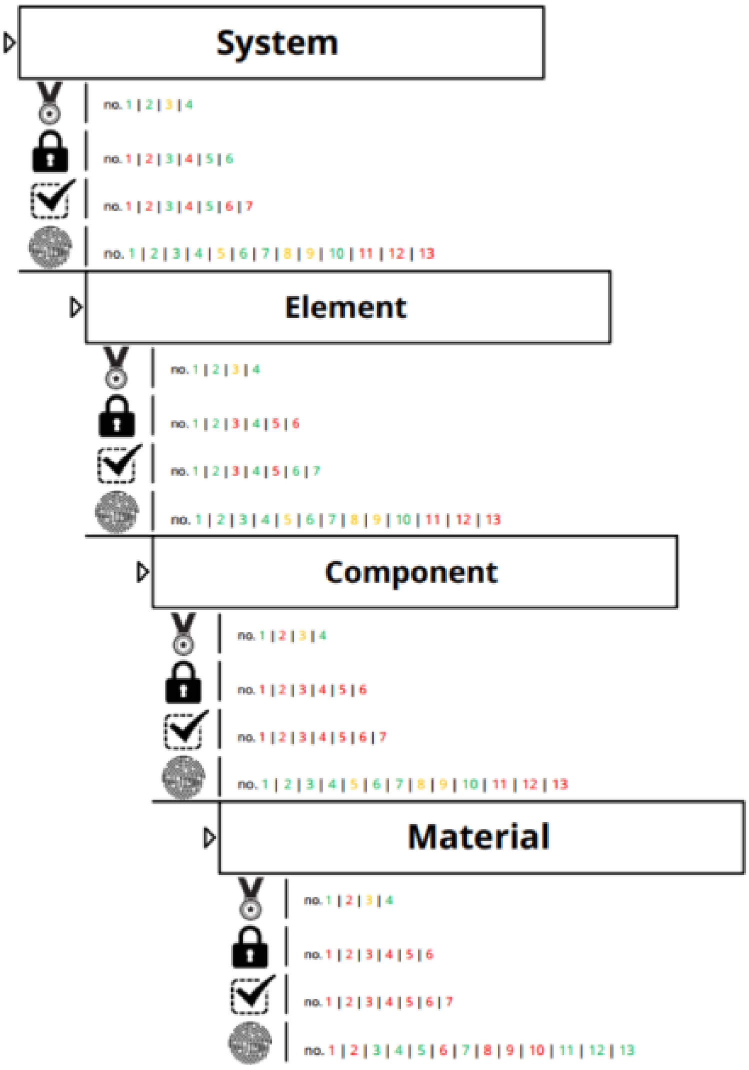

Figure 19: Type of data to be entered corresponding to different levels (de Architekten Cie, 2017)

2.2.3 Stakeholders involved in Material Passports

According to LLMNT material passport's report, the stakeholders are classified into four groups based on the life cycle of a building (Debacker and Manshoven 2016) are shown in figure 20. These stakeholders need to be included in this research as they directly work with material passports. The core actors are the actors who provide data input to the material passport. The actors have different data input and requirements when compared to each other and can be seen in table 6.

Figure 20: Stakeholders related to Material Passport (de Architekten Cie, 2017)

Table 6: Different Data Input and requirements by different stakeholders (Rudolphi, 2018; de Architekten Cie, 2017)

		Data Input	**Data Requirements**
Design Phase	Designer	Location Manual for disassembly Name and Code	Performance Size Weight Name and Code Supplier Certification Technical Lifespan Composition of material Material Toxicity
	Supplier/ Manufacturer	Product Assembly Manual Supplier Performance Weight Size Name and Code Certification Technical Lifespan Composition of Material Material Toxicity	
	Advisor		Performance Size Weight Code + Name Supplier Certificates Technical Lifespan Composition Material Re-use Loop Material Toxic Level of Material
Build Phase	Contractor	Management log Maintenance log	Instruction Manual Assembly (Log) Supplier
Use Phase	Facility Manager	Management Log	Manual Maintenance Manual Management Log Maintenance Supplier Location
	Maintenance	Maintenance Log	Manual Maintenance Manual Management Log Management Supplier Location
Reuse Phase	Recycler	Financial Value Log Disassembly	Circular Performance Disassembly possibilities Date Release Manual Disassembly

			Log Maintenance Log Management Log Assembly Supplier Location Completion Owner Technical Lifespan Composition of Material Re-use Material Loop Toxic Level of Material
	Urban Miner	Financial Value Log Disassembly Owner Secondary supplier	Circular Performance Disassembly possibilities Date Release Manual Disassembly Log Maintenance Log Management Log Assembly Supplier Location Completion Owner Technical Lifespan Built Material Material Toxicity

2.2.4 Information exchange in the Material Passports

It is essential to understand the factors that are influencing information exchange to develop a strategy to achieve qualitative information exchange. According to the research of Li and Lin (2006), several factors present have a strong influence on the willingness to exchange information; they are; trust among the actors within the supply chain industry, a shared vision and uncertainty of the industry suppliers. Damen (2012), in her research, states that the material (resource) passport's information exchange system should contain five format elements, i.e., provision, access, storage, quality, and the presentation of information.

- **Provision of Information:** As no single actor has control over the entire supply chain, it is essential to cooperate among different actors to facilitate the exchange of information. This cooperation can be attained through the process of negotiation. (Jain & Benyocef, 2008). Many departments within an organization must provide the requested details for the content passport (Rudolphi, 2018).

- **Storage of Information:** Due to the adoption of new digital technologies such as sensors, IoT etc., there is a tremendous growth of data volume. (Zhing, Newman, Huang & Lan, 2016). The research by Benchini et al. (2008) suggest storing the data locally and transferring the information only when requested through a pull function to a centralized database since the organization is responsible for its data provided for a material passport.

- **Access to Information:** One of the major hurdles that the supply-chain industry facing in information exchange is confidentiality issues (Lee & Wang, 2000). Companies could be unable to exchange data due to the risk of information being leaked, which may lead to strategic action by a competitor. (Smith et al., 2017). The data can be stored in private serves, and only the traceability of data is provided to others to guarantee the confidentiality of data. In this structure, a data-trustee is necessary as a trusted third-party owner of the data (Bechini, Cimino, Marcelloni and Tomasi 2008).

- **Quality of Information:** The quality of information is based on the factors such as time, accuracy, credibility and adequacy of the exchanged information. Trust among the actors within the supply chain and a shared vision is essential to improve the quality of information sharing (Li & Lin, 2006).

- **Presentation of Information:** It is essential to present the data/information in a unified model as there is no central authority within the supply chain (Sahin & Robinson, 2002). The data is to be understood at each and every phase of the supply chain; hence unification of information is needed (Lambert, 2001).

2.2.5 Opportunities

Material Passports can help reduce the negative impact on the environment by the built environment as they facilitate the materials' resue. They are essential for exchanging valuable information within the value chain. The information available on the platform will allow contractors, subcontractors and suppliers to communicate, cooperate and collaborate. It gives a better insight into the demolition/reuse phase stakeholders as to which element or material can be reused or remanufactured. Material passports will create new roles and business strategies within the circular economy (Debacker & Manshoven, 2016). Rudolphi (2018), in his exploratory research, has listed several other opportunities as given in table 7.

Table 7: Opportunities for material passport (Rudolphi, 2018; Kedir et al., 2021; Miu, 2020; Luscuere, 2016)

Provision of Information	1. The material passport improves the data continuity among the various building lifecycle phases. 2. Reduction in cost as the required information is collected and stored than collecting specific information separately for the process every time when needed.
Quality of Information	1. Improving the management of data during the lifecycle of the building 2. Information regarding the extraction of materials from building 3. Determination of Real value of the materials
Presentation of Information	1. Uniform/Standard parameters for data to be used in material passports

2.2.6 Barriers

Several barriers were stated by Debacker and Manshoven (2016) in their research. The fragmented nature of the construction industry as well as EU policy results in less or no integration. Lack of data standardization and robustness over the value chain is one of the barriers. Sharing the materials' intellectual property and product data is still a major barrier, but this is necessary to implement material passports successfully. At present, quality assurance and certifications for reclaimed products are not available. Rudolphi (2018), in his exploratory research, has listed several other barriers as given in table 8**.**

Table 8: Barriers in implementing for the material passport (Rudolphi, 2018; Kedir et al., 2021; Miu, 2020; Honic et al., 2019;)

Provision of Information	1. No incentive for providing the data 2. Non-availability of the data 3. Some actors do not want to be transparent due to fear of losing competitive edge by sharing sensitive information (Confidentiality issue).
Storage of Information	1. Ownership rights on the data
Access to Information	1. Every actor cannot have complete access to all the data present on the material passport. It is important to have different access levels to see different data.
Quality of Information	1. Managing the quality assurance of the data in the material passports. This raises the question of when data is inaccurate, who is liable for the aftermath. 2. No standard for a material passport
Presentation of Information	1. Lack of uniformity/standard in the data within the built environment.

2.2.7 Conclusion

The limitation posed by the current linear economic model can be addressed by adopting the principles of Circular Economy. As defined earlier, a Circular economy, together with related principles, is an economy that is designed to be regenerative and promotes the use of renewable sources of energy. Through meticulous design, the concept of circular economy aims to reduce, track and remove harmful waste. This can be achieved by adopting systems thinking and reinventing the supply chain to create a closed-loop by reusing, refurbishing, repairing and recycling the products and materials. For this to become successful, it is essential to have information regarding material flow, products design and end-of-life scenarios. This will eventually lead to the production of a huge amount of data that must be stored and utilized efficiently and effectively to establish a link between various material cycles. However, the industry lacks an information exchange system which is seen as a major barrier for successful Circular Economy initiatives.

The novel concept of Material passports was introduced to overcome this information exchange barrier in the Circular Economy. These Material passports are instruments for tracking the value and bringing the residual value of the materials to the market. Furthermore, sharing information related to the materials' intellectual property and products' data is a barrier. Perhaps for the material passports' success, certification or quality assurance for secondary materials is necessary. It is also important to transit toward a circular economy from the current linear economic model to facilitate new information flows and create closed loops.

2.3 Blockchain Technology

Bitcoin is the first application of blockchain. Satoshi Nakamoto (2008) created the first electronic distributed peer-to-peer (P2P) payment system, Bitcoin. A trusted third party is not necessary for this payment system. The bitcoin blockchain is the core technology behind this and is a database that records the transactions which are carried out within the network. This database is distributed and tamper-resistant (Atzori, 2015). Often, bitcoin and blockchain are confused with being synonyms, but it is essential to understand that bitcoin is one application of blockchain technology (Brenig, Schwarz, and Rückeshäuer, 2016).

"A blockchain is essentially a distributed database of records or public ledger of all transactions or digital events that have been executed and shared among participating parties. Each transaction in the general ledger is verified by the consensus of a majority of the computational power of the network." (Crosby, Nachiappan, Pattanayak, Verma, & Kalyanaraman, 2016, p. 7)

To understand the key aspects, working mechanism and the application of blockchain technology, it is essential to know about the various parts of the blockchain technical model. The Blockchain technical model consists of five layers, namely: Data, network, consensus, contract and application layers.

a. Data Layer: This layer of blockchain represents the physical form of blockchain technology. It comprises functions such as data block and chain structure, hash function, Merkel tree, timestamp and asymmetric cryptographic encryptions (Xinyi et al., 2018)
b. Network Layer: The network layer is a P-2-P network (peer-to-peer or point-to-point) that brings life to the blockchain by connecting all the nodes. In the Blockchain, the network layer executes the connection and communication between various nodes present in the network (Xinyi et al., 2018).
c. Consensus layer: This layer is one of the core aspects of blockchain technology. The consensus layer consists of consensus algorithms that bring the nodes in the network to a consensus on the block's validity. The main aim of this layer is to ensure the consistency and correctness of the nodes and the construction and validation of blocks. Some of the commonly used consensus mechanisms are Proof-of-Work (PoW), Proof-of-Stake (PoS) etc.
d. Contract Layer: The business logic and algorithm in the blockchain is situated in the contract layer. A smart contract can be created, customised, and realised by combining scripts, functions, and data in the blockchain network. The rights, conditions and responsibilities of various actors involved in the transaction are stipulated in the smart contract. The smart contracts will be executed automatically without the involvement of a third party once the agreed-upon execution criteria are met.
e. Application Layer: This layer serves as the network's user interface. It is built on top of the other layers. It is through this layer; the user can interact with the blockchain network.

2.3.2 Centralized Database Systems

In a centralized database system (traditional database), all the data is stored at a single location. The data can be maintained, modified and accessed only from that location. Institutions or organisations mainly use this type of database system to centralise the tasks. Multiple users can access the data from the central database simultaneously via the internet/intranet (Choudhury et al., 2018). However, in such a system, a single central authority is present who controls the actions in the system. Hence the system becomes vulnerable if the system admin is compromised. The centralized system is prone to cybercrimes such as intrusions, breaches and hacking as the data is stored in a single location. In case of power outages or data loss, recovering the information is nearly impossible. Hence, backup and disaster recovery techniques are required (Acharya, Yerrapati & Prakash, 2019).

2.3.2 Characteristics of Blockchain

In this section, different characteristics of the blockchain are explained to understand the technology better. In table 9, different characteristics of blockchain technology from different studies are compared.

Table 9: Characteristics of Blockchain

Correspoding Characteristics	Puthal et al., 2018	(Zheng et al., 2017)	(Labazova et al., 2018)	(Xinyi et al., 2018)	(Morarbito, 2017)
Distributive Nature	P-2-P	Decentralisation	Decentralized	Decentralization	Decentalisation
Transparent	Transaction	Read Permission	Reading Access	Openness	Provenance
Immutable	Consensus Mechanism	Persistency and Auditability	Consensus Mechanism	Verifiability and traceability	Irreversibility
Security	Cryptography	Digital Signature	encryption	Security	Trust

First, the network structure is described, followed by ledger structure, transaction mechanism and consensus mechanism of blockchain.

2.3.1.1 Distributive Nature

A blockchain's network is classified as a distributed network. This distributive nature is one of the salient features of Blockchain technology (Swan, 2015). The innovative feature of blockchain is that every node on the network will have the ledger's copy. This ledger will have all the transactions recorded. This ensures that no single participant can tamper with the data recorded on the blockchain as the power is distributed among the network with no single point of control and rules out the need for a central database. Even though every node in the network will have a copy of the entire ledger, the information can only be accessed by the nodes which have the key (Spielman, 2016). On the other hand, we have centralized database storage systems, which are prone to cybercrimes such as intrusions, breaches and hacking. The distributive nature of blockchain makes it difficult to carry out such attacks on the network (Xu, 2016).

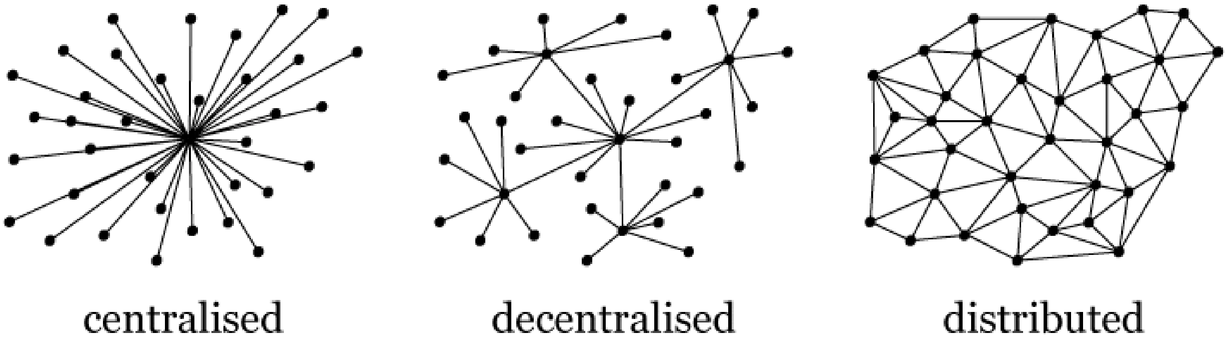

Figure 21: Types of Network Architecture (GitHub, 2018)

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A blockchain can be considered as a database that records the transactions which are completed and distributed among the network's participants. The blocks in the blockchain contain the records of the transaction. Figure 19 gives an overview of the chain of blocks. The block mainly constitutes two parts, the header and body. The block's header holds the information such as block version, Merkel tree root hash, timestamp, nounce and hash of parent block. The block's body contains the transactions and their details (Zheng et al., 2017).

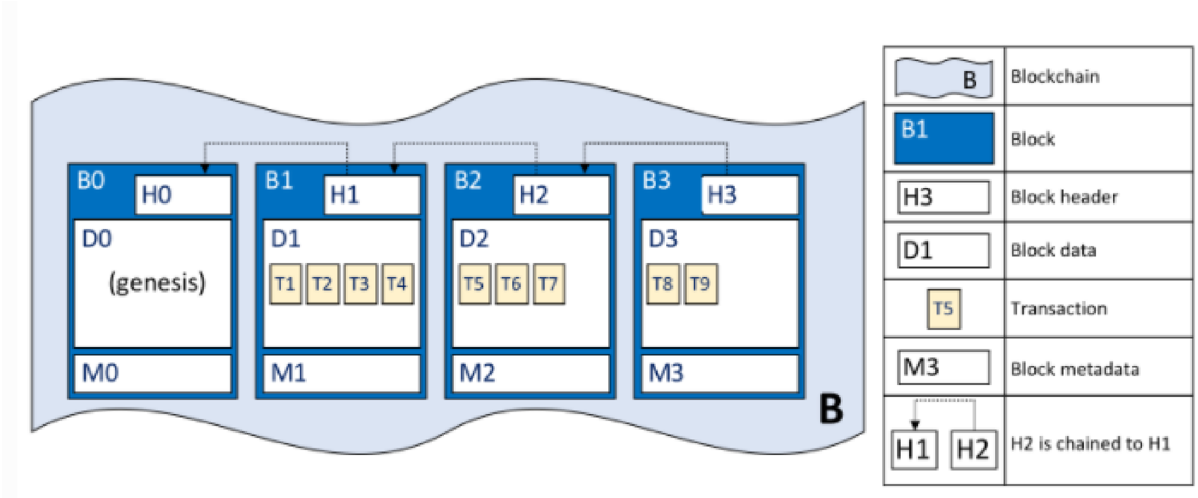

Figure 22: Block Architecture (Ledger – Hyperledger-fabric docs main documentation, 2021)

The transaction has to undergo the signing and verification phase before it can be updated on the blockchain. In the signing phase, the encryption of the data takes place with the help of a private key, and during the verification phase, the decryption is done via using a public key. The verification is done to ensure that the same transaction is not carried out twice (Morabito, 2017). In this way, the transaction that are updated to the ledger is governed by passing the duties to nodes that verify these transactions independently (Tasca, Thanabalasingham, & Tessone, 2017).

Transaction Mechanism in Blockchain

Morabito (2017) describes the blockchain network's transaction mechanism in five phases, namely:

- **Transaction Definition:** The sender initiated the transfer and broadcasted it to the network. The transaction contains information like the public address of the receiver and transaction value. The digital signature of the sender authenticates this transaction.

- **Transaction Authentication:** Once the transaction is broadcasted among the nodes in the network, these nodes will verify by decrypting the digital signature. Until a block is formed, the authenticated transactions wait along with pending transactions.

- **Block creation:** The authenticated transactions that were pending are updated into the ledger as a block. This block will be broadcasted in the blockchain network for validation.

- **Block Validation:** The block which was broadcasted is received by the validating nodes. Then the block is validated through an iterative process. A majority of the network's consensus is necessary for the validation of the block. The validation techniques used differ based on the type of blockchain network. For example, Ethereum uses 'Proof-of-Stake' while blockchain uses 'proof-of-work (Zheng, Xie, & Dai, 2016).

- **Block chaining:** Once the validation of transactions is complete, the new block is chained into the blockchain.

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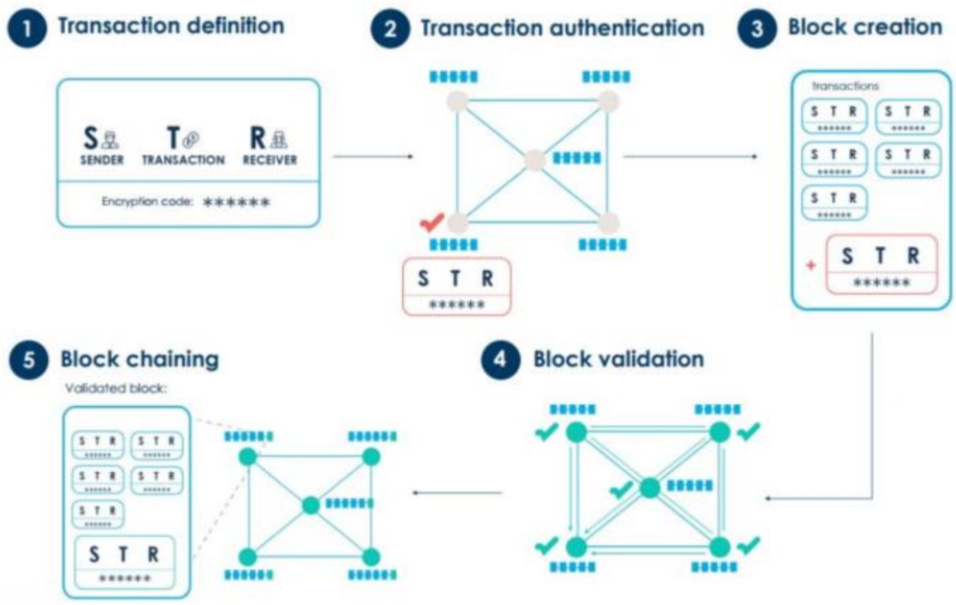


Figure 23: Transaction overview in Blockchain (Frøystad & Holm, 2015)

2.3.1.3 Security (Cryptography)

Cryptography is developing protocols to prevent third parties from accessing the confidential data that is being transacted. The two primary cryptographic functions that make blockchain safe and running are asymmetric key cryptography and hash functions. In asymmetric cryptography, pair of keys named public and private keys are used for encryption (Morabito, 2017). The digital signature is a major part of asymmetric cryptography. At the same time, hash functions use a cypher to generate a hash value from plain text. The hash functions' primary role is to link one block to another and maintain data integrity. Hence, cryptography is the core of blockchain technology which makes it reliable and immutable. (Spielman, 2016)

The public and private key pairs in blockchain technology are used for digital signatures and data encryption (Kuan Hon, Palfreyman, & Tegart, 2016; Spielman, 2016). By generating a unique string of numbers and letters, the public key creates a public address for the user, which can be shared. On the other hand, the private key is used to digitally sign the transaction. This signature is used to authenticate the transaction and broadcast it on the blockchain network (Spielman, 2016).

2.3.1.4 Consensus Mechanism

The blockchain network is transparent and robust, as the network is designed in such a way that all the participating nodes will contain the ledger's copy. Upon verification and authentication of the transaction by the nodes, it is nearly impossible to tamper with the data. This makes it immutable (Tasca, Thanabalasingham, & Tessone, 2017; Morabito, 2017). Blockchains are very dynamic as they keep on updating. Hence they require a reliable, secure, efficient and real-time mechanism to ensure that the transactions occurring in the network are legit. This trust in the blockchain network relies on a consensus mechanism. A consensus mechanism is a process most of the network, or the nodes with the most CPU power or the nodes with the most currency etc. depending on the consensus mechanism, agree on the ledger's status and data's validity (Morabito, 2017; Kuan Hon, Palfreyman, & Tegart, 2016). This eliminates the need for a trusted third party to validate. The main types of consensus mechanisms are as follows:

- **Proof of Work:** To make the bitcoin network secure and consistent, Nakamoto proposed the consensus protocol Proof-of-Work (PoW). In this protocol, the nodes compete with other nodes in the network to solve the complex puzzle and add the block to the true chain. These nodes are known as miners. The PoW protocol requires that the hash of the block header contains a certain number of Zero bits when the nounce is added to the header of the block (Nakamoto, 2008). The miners try to find this nounce to obtain the desired hash of the block header. When a particular node obtains the desired hash value, the block is broadcasted to the other nodes in the network, who validate the correctness of the hash value. Upon validation, the block is appended to the blockchain (Zheng et al., 2017).

- **Proof-of-Stake:** In Proof-of-Stake (PoS) consensus, the node has a higher probability for getting selected to validate the block if the node (user) has a higher stake in the network. This is based on the assumption that users with a higher stake are more likely to provide truthful information w.r.t the validation process (Tasca & Tessone, 2019). The nodes will receive an incentive for validating the blocks. However, they would lose some amount from their stake if the block is not appened onto the existing chain (Puthal et al., 2018).

- **Practical Byzantine Fault Tolerance (PBFT):** This consensus protocol is based on voting. PBFT consensus protocol is an annulus to distributed networks. The transactions keep flowing through the nodes in the network, and these nodes validate and sign these transactions. Once most responses to the transaction are obtained, the consensus is achieved, and the transaction is validated (Morabito, 2017).

2.3.2 Types of Blockchain

The bitcoin developed by Satoshi Nakamoto (2008) is based on a public blockchain. However, the public blockchain is not suitable for various other applications that are being developed today, which led to the creation of other types of blockchain. Mainly, there are two types of blockchain networks—public and private.

Public Blockchain: The public blockchain is transparent and open. Hence, anyone can access, read, write or participate invalidation (consensus) process of the transaction. It is a P-2-P network that is completely public, decentralised and distributed, which is not under anybody's control. The use of encryption methods like asymmetric key cryptography secures the blockchain network. However, there are certain drawbacks such as high maintenance and operational costs, low scalability and slow transaction speed. The most common applications of public blockchain are Bitcoin, Ethereum etc.

Private Blockchain: It is open to a single organisation or multiple organisations to facilitate information/data exchange among themselves. For a node to read or write, access or use the data in the blockchain network, authorisation is required. The network that controls the access determines the participation of nodes in the network. This makes the network slightly inclined towards centralisation. However, it has high transaction speed, lower transaction costs and better data security. One of the major applications of private blockchain is Hyperledger Fabric (Zhang et al., 2018).

Besides being public or private, a blockchain can be categorised as permissionless or permissioned. As a result, there are four types of blockchain: Public Permissionless, Public Permissioned, Private Permissionless and Private Permissioned (Acharya, Yerrapati & Prakash, 2019)

Public and Permissionless	Public and Permissioned	Private and Permissionless	Private and Permissioned
Open and transparent.	Open and restricted.	Restricted yet read transparent.	Restricted (hybrid approach).
Write all and read all.	Write all and read restricted.	Write restricted and read all.	Write restricted and read restricted.
Everyone can join, transact, read, and audit.	Everyone can join and transact, but only permissioned users can read and audit.	Everyone can join, nobody can transact, and everyone can read and audit.	Nobody can join, transact, read, and audit.
Anyone can download the protocol and participate with validate transactions.	Anyone who meets the predefined criteria can download the protocol and participate with validate transactions.	Anyone in the network can participate and validate transactions. However, this is only within the enterprise.	Only consortium members can validate the transaction.

Figure 24: Types of Blockchain (Acharya, Yerrapati & Prakash, 2019)

2.3.4 Challenges

At present, Blockchain is still in its early phases of development. Despite the advantages that were discussed in this chapter, blockchain technology has certain challenges and limitations. This technology must overcome certain challenges and limitations to acquire widespread adoption. The challenges that are hindering the use of blockchain technology are described below: (Mthethwa, 2016; Morabito, 2017; Zheng et al., 2017)

- **Scalability:** The scalability issue of blockchain is considered one of the major challenges. The nodes in the network need to store all the transactions in order to validate them, thus leading to the requirement of high storage space. Besides this, the slow consensus process and limited block size (1Mb) majorly contribute to the scalability issue. However, due to these factors, only six to seven transactions are confirmed per second with a high transaction fee.
- **Awareness and Understanding**: Most individuals or organisations are neither aware of the technology nor understand it completely. Hence, it is difficult for someone to implement the technology when they do not fully comprehend it. Therefore, this can be considered as one of the major challenges for implementing blockchain technology.
- **Privacy and Security**: Blockchain doesn't offer complete privacy for the users. The users of the network use public and private keys to transact and these keys protect the true identity of the user from being exposed. But, the blockchain does not give any guarantee for transactional privacy (Zheng et al., 2017). Besides this, some studies show that the true identity of the user can be revealed by linking the bitcoin transaction even though the users are behind firewalls.
- **Regulations and Governance:** Blockchain technology is a relatively new and rapidly advancing technology due to which the regulations struggle to keep up with the technology. It takes time for the governing bodies to accept and adapt to new technologies like blockchain with regulations.

- **Energy Consumption**: On average, the mining process for 1 Bitcoin consumes energy that is equivalent to the energy consumed by an American household for two years. It is also predicted that a bitcoin transaction consumes 80,000 times the energy required to process a credit card transaction.

2.3.5 Misconceptions of Blockchain

Due to the exponential rise of Bitcoin and the number of scientific studies being published on a blockchain, it can be said that the blockchain is at the pinnacle of its hype cycle. However, in many cases, encrypted or not, traditional databases tend to be suitable in many cases than a blockchain-based application. Besides this, there are certain misconceptions about the potential of blockchain technology due to its novelty and hype.

- **Blockchain is trustless:** The blockchains assists in reducing the requirement for trust. However, they cannot eliminate the trust factor. At the very least, trust is placed on the system, such as Cryptography or in the case of permissioned networks, the network operators need to be trusted. (Hileman & Rauchs, 2017).
- **Blockchain is immutable:** Similar to the blockchain's 'trustlessness', it is not completely immutable. The blockchain follows an append-only data structure in which the data can be added to the blockchain but not remove from it. Theoretically, if the nodes have decided to collude, the blocks comprising the transactions can be reverted.

2.3.6 Conclusion

The innovative blockchain technology opens up new doors for improving Material Passports that are based on the characteristics of blockchain. The Real Estate and Built Environment sectors can have a huge impact by implementing blockchain as it can be used to register assets. Through the use of blockchain, transparency, traceability and other issues related to information exchange can be addressed and enhanced the material passports. With the use of a distributed, consensus-based, tamper-resistant ledger, the material can be tracked from its origin to its transformation during the lifecycle of a building. At present, this innovative technology faces some challenges and limitations. Blockchain must overcome certain hurdles like scalability, energy consumption, awareness and understanding etc., in order to acquire widespread adoption. However, a private permissioned blockchain Hyperledger Fabric's architecture aims to resolve several challenges that the public blockchain poses. More about Hyperledger Fabric is discussed in the coming chapter.

3 Blockchain-based framework

3.1 Introduction

As we discussed in the previous chapter, blockchain technology provides opportunities to enhance the application of material passports based on key features such as its distributive nature, transparency and traceability, immutability and security. However, there are several challenges that this novel technology has to overcome, namely, privacy and security issues, scalability, unsustainable consensus mechanism (computing power) and lack of governance. These challenges hinder the application of blockchain in a business case (Davies, 2020). According to Davies (2020), a blockchain expert and Hileman and Rauchs (2017) have listed certain requirements for a blockchain network from a business/enterprise point of view:

- The consortium requires a blockchain that allows them to govern who enters the network and the ability to confirm a new user's identity.
- Swift transactions and scalability is a requirement for enterprises
- The consortium must pre-define the access control list for the exchange of sensitive data
- A certain level of privacy is required for transaction data
- A resilient network

Davies (2020) states that Hyperledger Fabric addresses the issues of a traditional blockchain and meets the enterprise requirements.

3.2 Hyperledger Fabric

Hyperledger Fabric (HLF) is an open-source blockchain-based platform developed by the Linux Foundation. The Hyperledger advocated a community-based approach for the development of a blockchain network. HLF's architecture aims at the several challenging aspects of blockchain, such as scalability, flexibility, resilience and confidentiality. HLF is the first permissioned blockchain that can execute the dApps written on standard programming languages. The architecture of Hyperledger Fabric has adopted an innovative Execute-Order-Validate approach for the flow of the transactions: (1) Executing a transaction and endorsing it (similar to validating the transaction in the blockchain), (2) Ordering the transactions through consensus protocol and (3) validating the transactions (Androulaki et al.,2018).

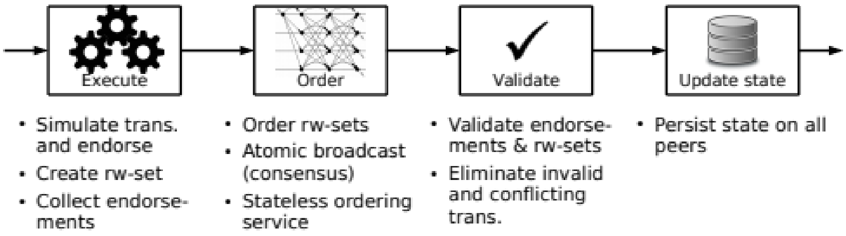


Figure 25: HLF architecture- Execute-Order-Validate (Androulaki et al.,2018)

3.2.1 Execution phase

In the execution phase, the transaction is executed by sending the digitally signed transaction proposal to the endorsers specified by the chaincode. This proposal is stimulated by the endorsers who do it by executing the chaincode. Upon completing the simulation, the transaction proposal is endorsed by the endorser and the proposal is sent back to the client in the form of a response. Until the endorsement policy is satisfied, the endorsements are collected by the client. Then, the transaction proposal with endorsements from the endorsers is passed on to the ordering service (Androulaki et al., 2018).

3.2.2 Ordering Phase

HLF features a node called ordering node that performs transaction ordering, and other nodes form ordering service. These ordering nodes do not take part in the validation phase or execution phase of the transaction (Androulaki et al., 2018). In the ordering phase, the ordering service nodes receive the endorsed transaction proposals from the client. The role of the ordering service is to order the transactions into well-defined sequence and pack them into blocks. These blocks will be distributed across the nodes in the network for validation (*The Ordering Service*, 2021). As a result, the blocks that the ordering service generates are final.

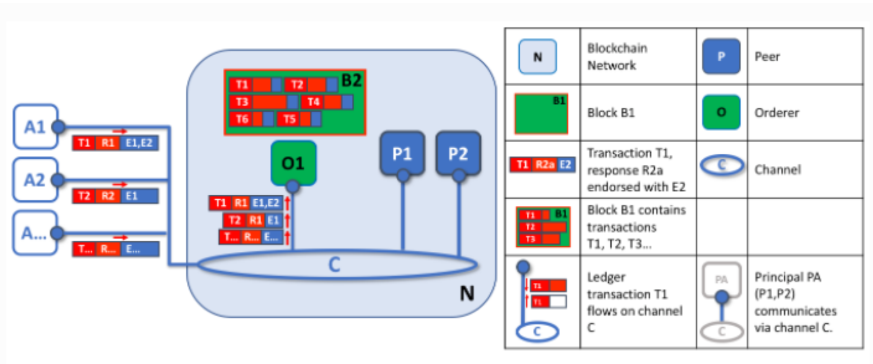


Figure 26: Ordering service (The Ordering Service, 2021)

3.2.3 Validation phase

In the validation phase, the blocks will be independently validated by every node. The validation of blocks is done by ensuring that the validated transactions have been endorsed by the required nodes as mentioned in the endorsement policy. If this condition is not satisfied, then the transaction is deemed invalid and disregarded (Androulaki et al., 2018; *The Ordering Service*, 2021).

3.2.4. Policies

The Policies are mechanisms that are developed to manage the Hyperledger Fabric's infrastructure. Since Hyperledger Fabric is a private permissioned blockchain, the actors participating in the network have the right to decide on the governance of the network before it is deployed. The members of the network can use these policies to control the aspects like which organisations have access to and update the blockchain network. In other words, any action that must be performed in the network is governed by policy.

3.2.5 Membership Service (MSP) and Certificate Authority (CA)

Since HLF is a permissioned blockchain, the identity of the actor has to be proven if he is willing to participate in the network. This is done through Certificate authorities (CAs) and Membership Service provider (MSP). The CA issues identity to the participating node by providing public and private key pairs that are used to prove their identity. On the other hand, MSP is the mechanism that allows the rest of the network to trust and verify the actor. The membership service provider (MSP) maintains the identities of all nodes in the system (clients, peers, and OSNs) (Androulaki et al., 2018). It is also responsible for providing credentials to the nodes participating in the network. These credentials are used for the authorisation and authentication of transactions in the network. MSPs are also the mechanism that assigns responsibilities and permissions to members of the network (MSP – HLF, 2021).

3.3 Hyperledger Fabric-based Material Passport framework

For developing a material passport, Hyperledger Fabric-based framework is proposed in this study to ensure security, privacy and confidentiality among the stakeholders who use the material passport. To develop a comprehensive system like Hyperledger Fabric-based Material Passports, software developers are required. Hence the framework developed in this thesis aims to be useful to develop Hyperledger Fabric-based Material Passport by Material Passport Developers. This framework will also help the stakeholders in the built environment to understand the information flow within the Hyperledger Fabric-based Material Passport.

The proposed framework, as shown in Figure 27 is divided into two parts, namely Front-end and Back-end. The front-end is what a user can see on the screen and interact with, or simply put, the Graphical User Interface (GUI). On the other hand, the application process that is not visible to the user such as, data processing, data storage, data transaction mechanism, etc., is known as Back-end.

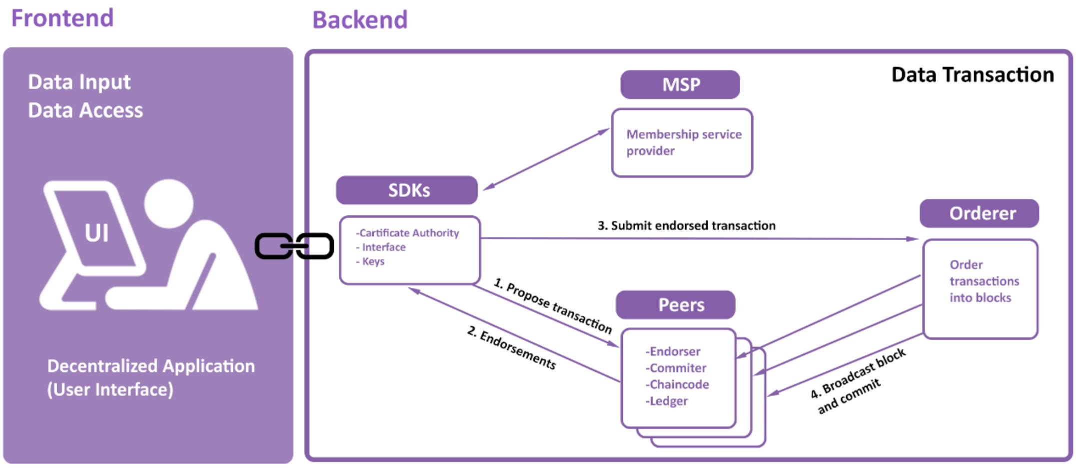


Figure 27 Hyperledger Fabric-based Material Passport Framework (own)

3.3.1 Front-end:

The front-end involves developing the User Interface(UI) for Material Passport. Through this UI, the stakeholders (such as client, contractor, designer, supplier etc.) can log in to the material passport application and enter/access the material data present in the network. To design a UI, the developer must gather the requirements from the users. In the case of Material Passport UI, the users' requirements will be the data that they input into the material passports and the data they have access to. This Data input and the Data requirements of users from the material passport are represented in figure 28.

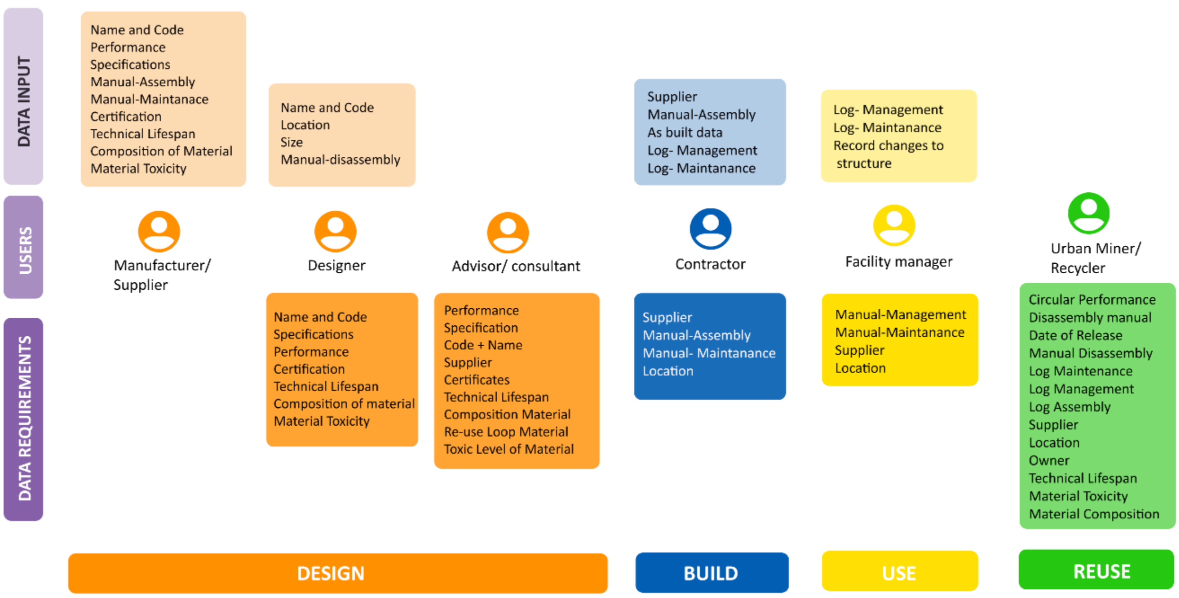


Figure 28 Data Input and Data Requirements by the users of Material Passport (own)

3.3.2 Back-end

For the Material Passport UI to provide the data required by the users, it has to interact with the application's back-end. Hence there must be a link between the front-end and back-end of the application for it to function correctly. This link is provided by Software Development Kits (SDKs). The SDKs will include libraries, documentation, codes, and processes required for the developers to develop the application. The Material Passport Developer can use SDK provided by Hyperledger fabric to develop the Material Passport application. These SDK provides Application Programming Interface (APIs) for transaction process, membership service and node traversal (Glossary-HLF, 2021). The Hyperledger fabric's SDKs supports various programming languages like Node.js, JAVA, Python and GO for developing application.

The Material Passport developer must utilise the Membership Service Provider (MSP) as it is a tool for managing the identity of the material passport users for authorisation and authentication. The MSP creates and distributes digital certificates to users with a unique user ID and their access rights. The user uses these certificates to sign transactions and gain access to blockchain resources. The access rights and legitimacy of the stakeholders in the blockchain network can be verified with the help of these digitally signed transactions.

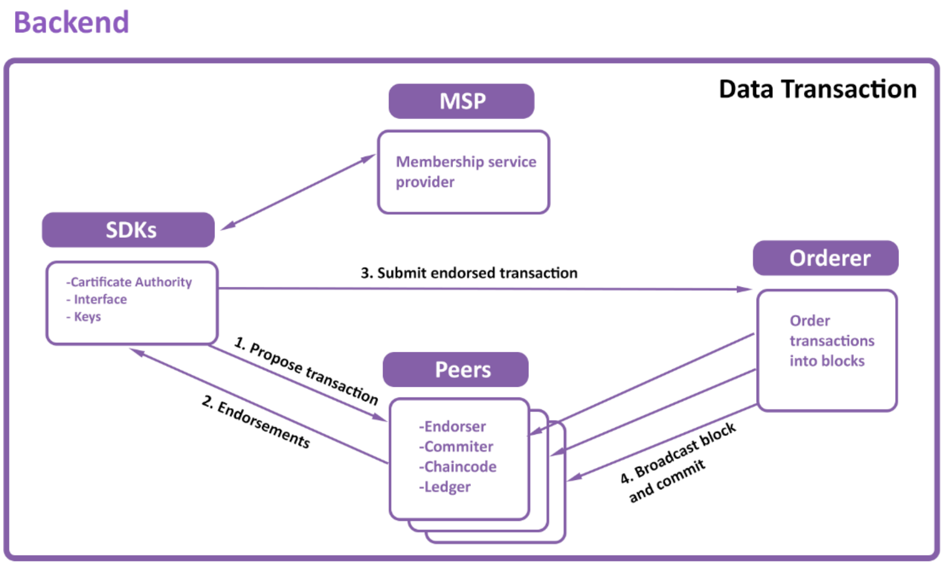


Figure 29 Back-end process of data transaction in Hyperledger fabric-based material passport (own)

In order to architect HLF, users (peers) of material passports such as supplier, contractor, client, designer etc., are made as an endorser, committer and orderer to ensure trustful, secure and smooth business operations. The Hyperledger fabric-based material passport's back-end architecture (transaction) with its users is shown in Figure 30. Further, the transaction flow of the data in the material passport is explained below. This is based on the Execute-Order-Validate approach of Hyperledger Fabric, as explained in section 3.2.

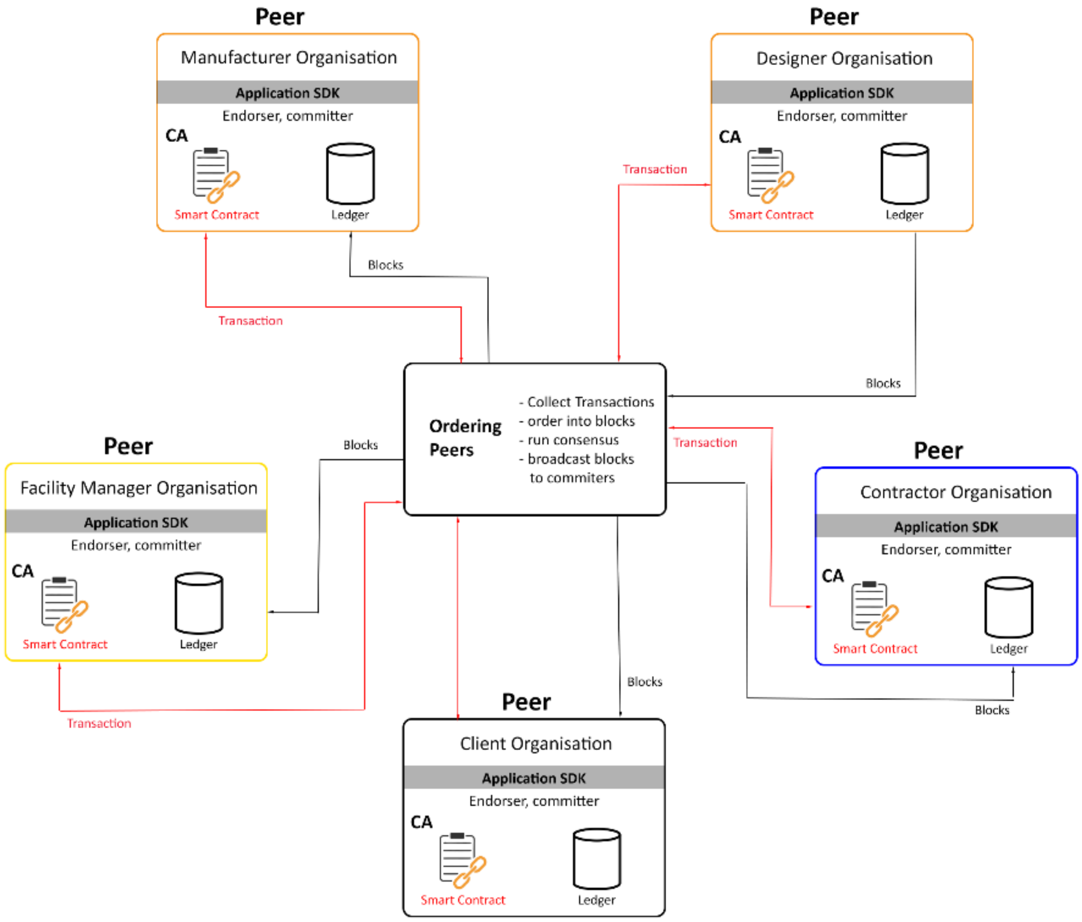


Figure 30 Hyperledger Fabric-based Material Passport Architecture(own)

Phase 1: A user from any of the parties such as supplier, consultant, designer, contractor etc., can enter the data (transaction) into the blockchain network through the Material Passport application to execute the function of smart contract, read, write or update data to ledger. This is encrypted with the user's private key and digitally signed by the user. This proposal is sent to different endorsers (supplier, consultant, designer, contractor etc.) for receiving endorsements.

Figure 31: User initiating the proposal via the app (Transaction Flow, 2021)

Phase 2: Before the execution of the transaction, the endorsing peers inspect the transaction proposal received from the user's application to check for its provenance, access rights and format. Upon completion of this, the transaction is simulated by executing the chain code (smart contract) to identify the read or write sets during the execution. Then the endorser digitally signs the proposal using his certificate and sends it to the user application in the form of endorsement.

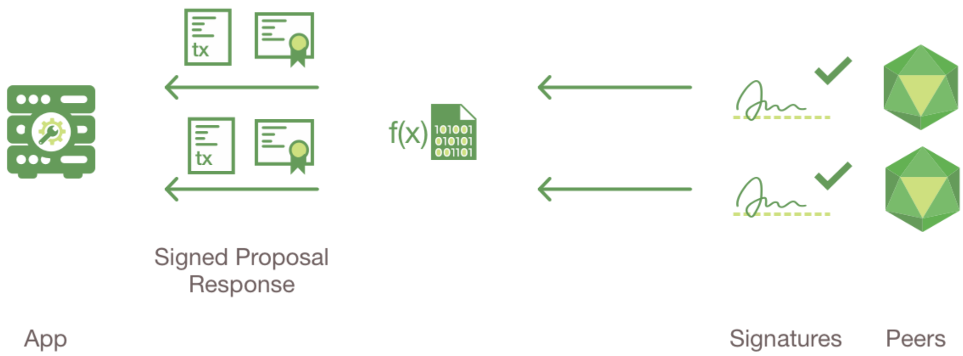


Figure 32: The user receiving the endorsed proposal (Transaction Flow, 2021)

Phase 3: The user's application receives the endorsed transaction proposal from all the endorsers. After this, the application inspects the read-write sets of the endorsements to make sure that all the endorsements it received have the same result. Later, the application sends these endorsed transaction proposals to the ordering service, where they get packed into blocks, which are then broadcasted to the committer peers (supplier, consultant, designer, contractor etc.) in the network for validation.

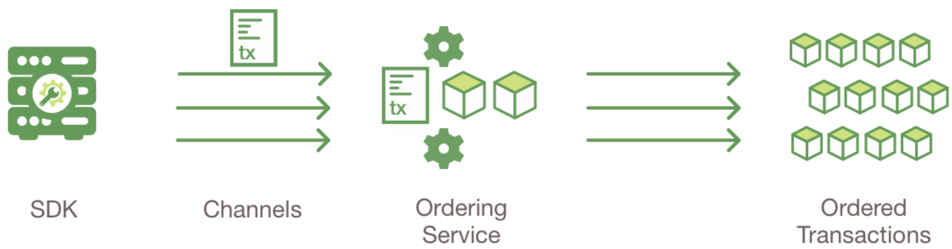


Figure 33: The app sends endorsed transaction proposal to ordering service to create blocks(Transaction Flow, 2021)

Phase 4: The committer peers authenticate the transaction owner before the transaction is validated. The validation occurs in three stages. In the first stage, the read and write sets are compared to the world state of the ledger to make sure that the data has not been altered since the transaction was endorsed. In the second stage, the transaction will be deemed invalid if it does not comply with the endorsement policy of the network. In the third stage, the block is appended to the chain and the transaction will be marked invalid (if it does not satisfy the first or second stage) in the block's transaction record. In the last stage, the transaction owner and concerned parties (users of material passport) are notified regarding the transaction result.

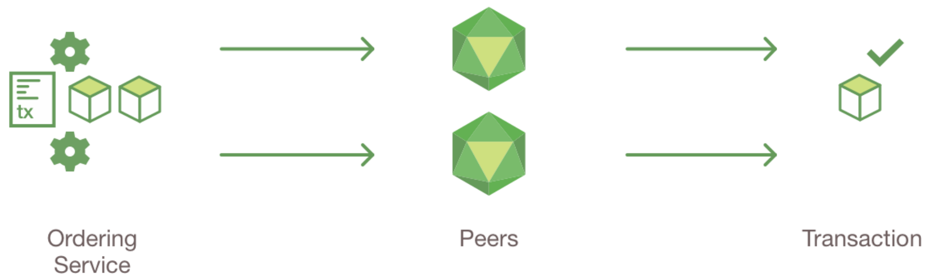


Figure 34: The blocks are broadcasted to peers for validation (Transaction Flow, 2021)

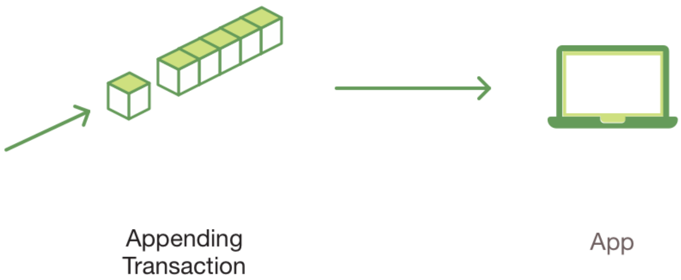


Figure 35: Upon validation, the block is appended to the ledger and notified to participants (Transaction Flow, 2021)

The sequence and process diagrams in Figures 36 and 37 depict the transaction flow of data within the material passports as explained in the four phases above. This helps the material passport developer understand the transaction flow of data within the material passport and develop the same.

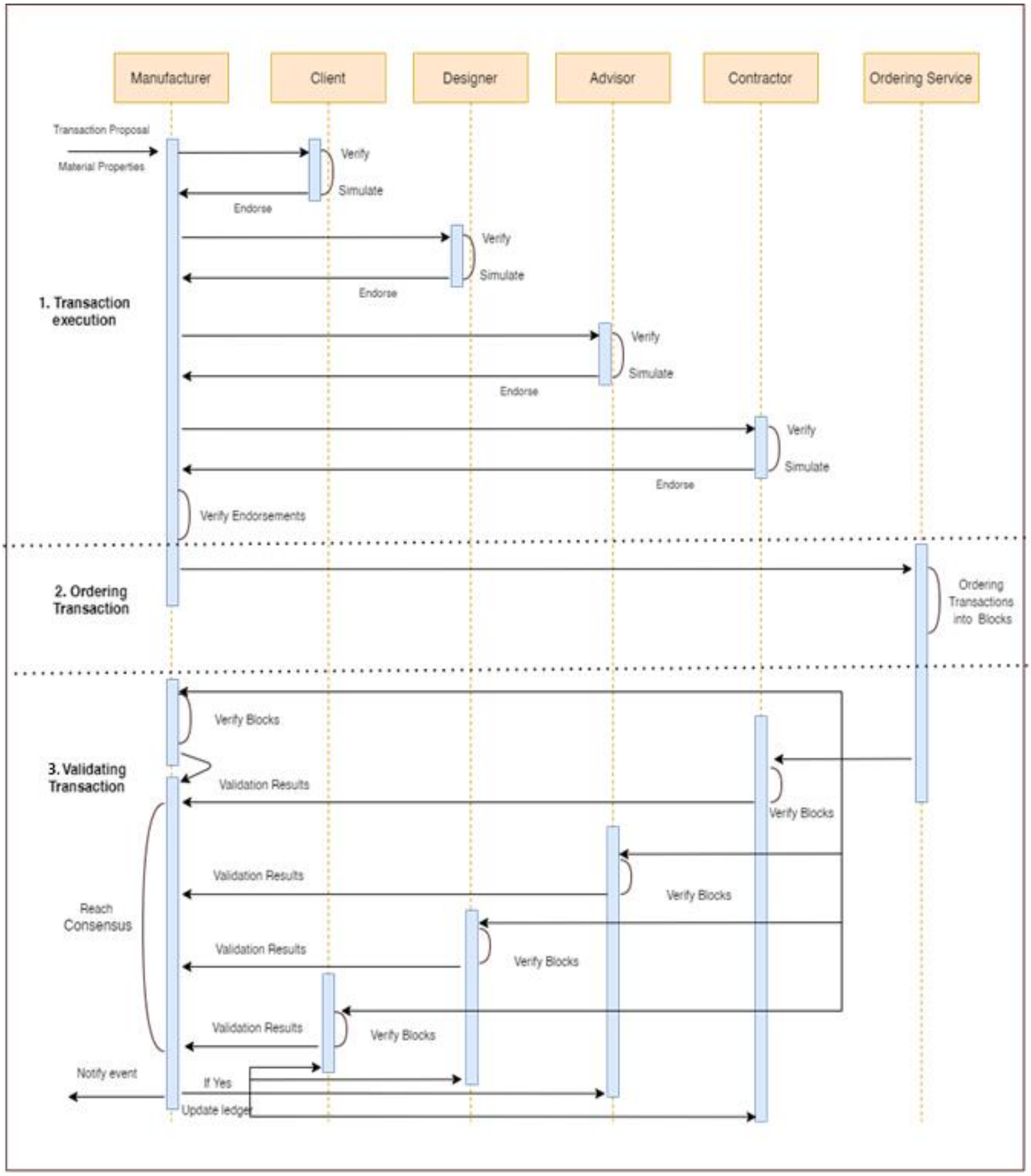


Figure 36 Sequence Diagram of transaction flow of data in Hyperledger Fabric-based Material Passport

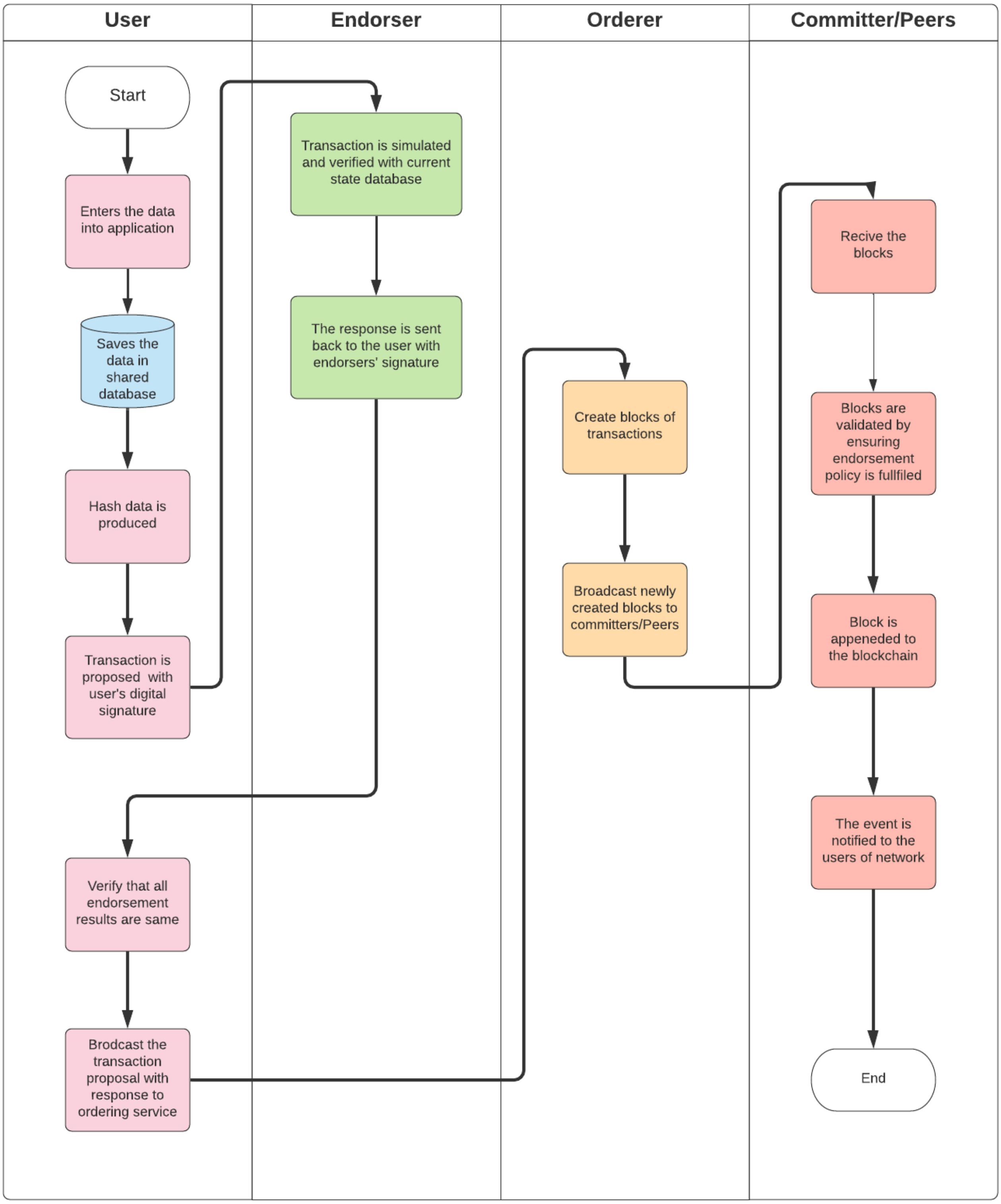


Figure 37: The process diagram of transaction flow of data in Hyperledger Fabric-based material passport (Own illustration)

3.4 Shared Database integration with Blockchain

Storing the data and retrieving it is the heart of the blockchain. The documents are relevant for material passports such as drawings, disassembly guides, bills of materials, contracts, ownership titles, certifications, invoices etc. which will account for several gigabytes (GB) of data. Storing such large files on the blockchain would be impractical as it leads to several challenges related to network latency and bandwidth, high computational and storage costs. This will have a negative impact on the performance of the blockchain network. Acharya, Yerrapati & Prakash (2019) propose a solution to this problem. The above-mentioned issues can be solved by using a shared database among the stakeholders who are anchored to the blockchain network. In such a system, the actual documents would be stored off-chain in the shared database, while the attributes of the document, such as document ID, a hash of the document and other metadata, is recorded on the blockchain network in the form of a transaction. This would not burden the blockchain network with a huge volume of data while still ensuring the document integrity and transaction history are preserved in an immutable manner on-chain (Acharya, Yerrapati & Prakash, 2019). Thus, the material passport developer must provide a shared database anchored to the blockchain network to store the documents off the chain while recording the documents' hash, metadata on-chain.

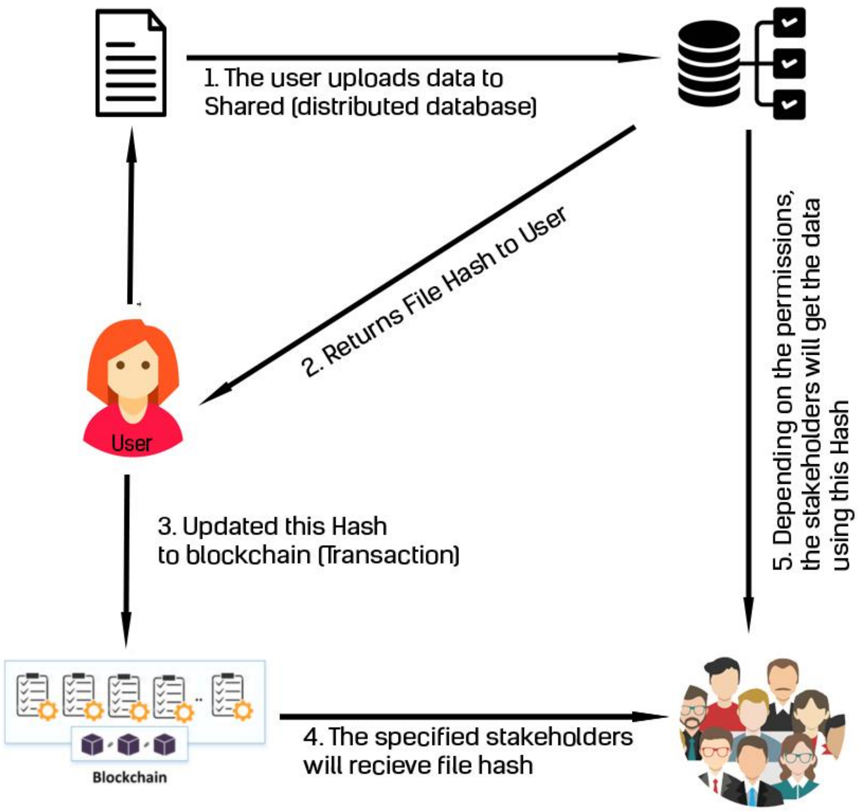


Figure 38: Process of sharing information in HLF based material passport

3.5 Conclusion

The Hyperledger fabric-based material passport framework was developed mainly to address the barriers of material passports and those of traditional blockchain. However, not all the barriers of material passports could be addressed by implementing blockchain technology. This section describes how the newly proposed conceptual framework of private-permissioned blockchain could improve material passports.

Provision of Information: Every actor participating in the network is responsible for the data they provide and will remain the owner of their data. Since the data is being provided to the material passports, the respective data hash will be stored in the blockchain. Hence, the participants in the network can see who is responsible for which data. This creates a social control that incentivises good data input (Morabito, 2017). Here, the blockchain network is just an instrument used to record changes made to the material passport.

Storage of Information: Not all the data is stored in the network. However, only the data hash is stored in the blockchain network while the data is stored in the shared database. This is to ensure that the provided data is not visible to all the participants in the network. The added advantage of adopting this step is that it reduces the payload of the network, thereby increasing the network latency. Once the data hash is validated and appended to the ledger, it becomes difficult to modify data as it can be detected by checking if the data hash is still matching (Morabito, 2017).

Access to information: To protect the confidentiality of the sensitive information provided to material passports, it is essential to have predefined access rights to users that only specific data is visible to them. These rights can be managed via a Membership service provider (MSP), Certificate Authority and Access Control List (ACLs) of the Hyperledger Fabric, making it unique.

Quality of Information: One of the most critical aspects of materials passport is the quality of the information that is being provided. As mentioned earlier, the transparent nature of the blockchain network allows its participants to trace who has provided the data, and this data can be viewed and verified by the participants who have access rights. These features of blockchain facilitate a form of social control within the network to provide quality information (Morabito, 2017).

However, there are some perceived disadvantages in adopting this framework which are:

- There are not adequate proven use cases. Most of the use cases are either proto-types or pilots. Some of the use cases from practice include IBM's FoodTrust, TradeLens in the shipping industry and Honeywell's new marketplace for selling new and used aerospace products (Case Studies – Hyperledger, 2021)
- An inadequate number of skilled programmers in the construction industry.
- The level of immutability offered by PoW in public blockchains cannot be achieved in HLF. However, the participants in the network are known and are bound by policy, which will give rise to a tamper-evident system. (Davies, 2020).

4 Demonstration and Validation

4.1 Demonstration

The Hyperledger Fabric-based Material Passport framework is compared with existing BIM-based material passports to demonstrate the efficacy of the developed framework. To understand the scenarios in a better way, a hypothetical case is described below.

Over the years, the number of students (Dutch and International) joining TU Delft has increased. This calls for more student accommodations as there is a severe shortage of housing for students in Delft. As a result, TU Delft decides to build 'de Orb', a circular student housing to accommodate 100 international students. This building will be designed by ABC architects and constructed by XYZ Bouw en Techniek bv. The client (TU Delft) wants to document the qualitative and quantitative data of the building materials through a material passport. This will help maintain the circular value of the materials at the highest level throughout the lifecycle of the building. To develop this material passport, TU Delft partners with material passport developer Kadaster BV.

To develop a material passport, it is essential to identify the stakeholders who will be using the material passport to provide/access information related to 'de Orb'.

a. Client (TU Delft): TU Delft, as a client, initiates the project by setting the functional scope along with circular demand. Generally, the client will be the owner of the asset.
b. Designers (ABC architects): The designer designs the building incorporating circular principles and strategies, making the building materials reusable after the end of life.
c. Contractors (XYZ Bouw en Techniek bv): The contractor engineers and constructs the building by procuring materials from manufacturers/suppliers.
d. Manufacturers/suppliers: Manufacture/supply raw or repurposed materials for 'de Orb'.
e. Facility Manager: The added responsibility of a facility manager is to operate and maintain 'de Orb' during the use phase lies with the facility manager.
f. Urban Miners: At the end of the life of the building, the urban miner reclaims the building materials and components of 'de Orb' to enable the reuse of these materials.

The following figures 33 and 34 show the data input and requirements of stakeholders involved in the construction of 'de Orb', respectively.

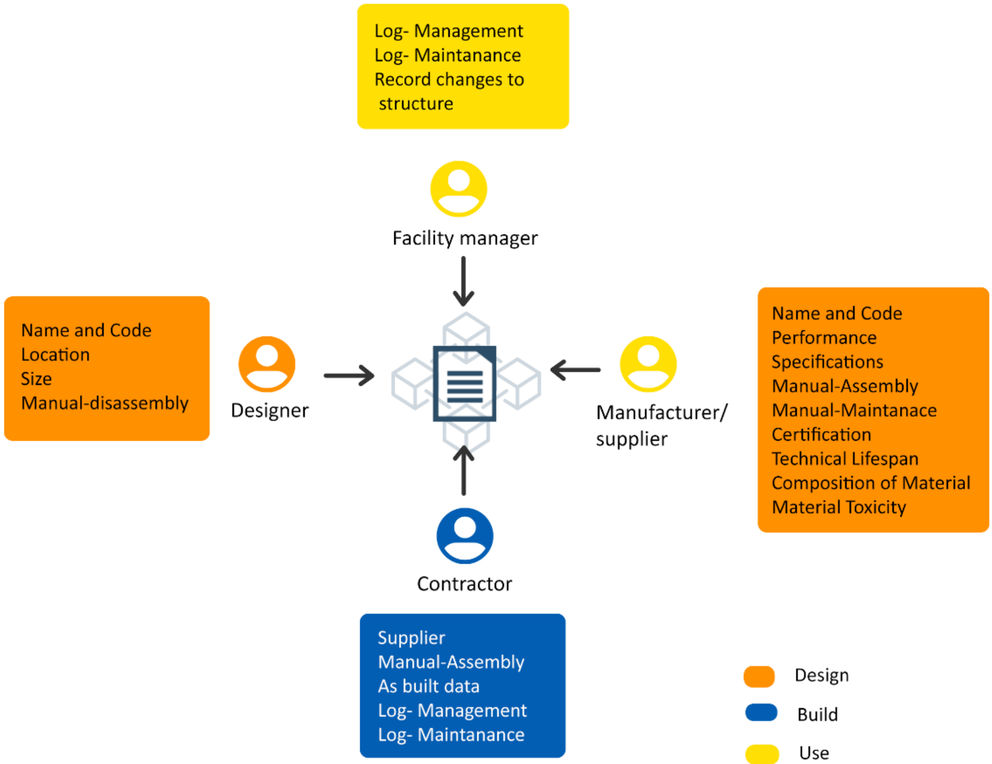


Figure 39: Data provided by various stakeholders for the material passport (own illustration)

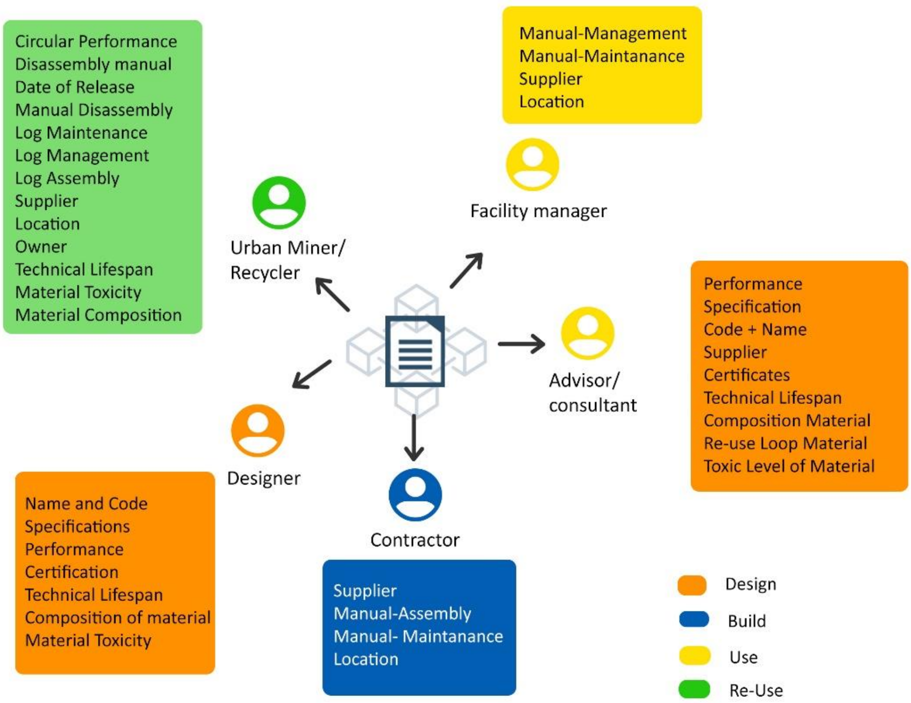


Figure 40: Data requirements of various stakeholders from material passport (own illustration)

The material passport developer, Kadaster B.V, comes up with two scenarios for material passports. The first one is the traditional BIM-based Material Passport (M Honic et al., 2019), and the second one is Hyperledger fabric-based Material Passport. The following parts will briefly describe the two scenarios.

4.1.1 Scenario A: BIM-based Material Passport

Building Information Modelling (BIM) assists in optimising the life cycle of buildings by offering various models and analyses. The BIM model consists of geometric and material properties, which is coupled/matched with the material database to produce a BIM-based Material Passport (M., Honic et al., 2019). The BIM-based material passport is a document comprising the quality and quantity of the materials used in the building, their recycling grade. It shows the building's impact on the environment. However, these Material passports are the result of the design stage of the building. The workflow for compiling a BIM-based Material Passport is shown in figure 36.

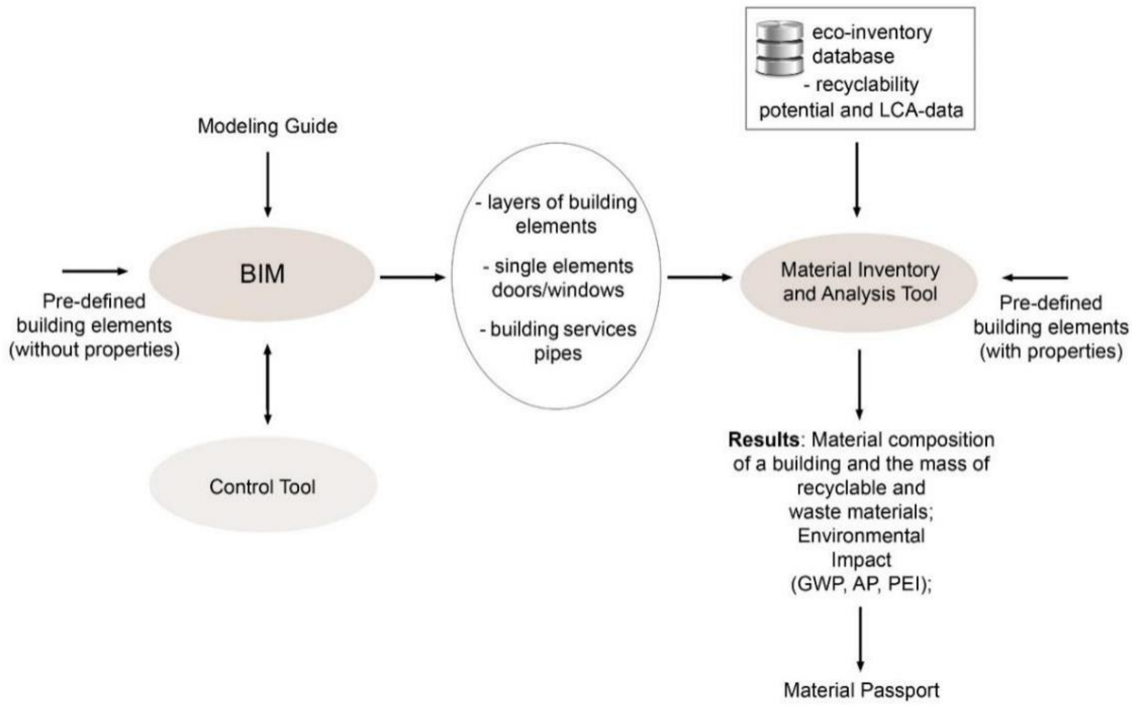


Figure 41: Workflow for compiling BIM-based Material Passport (M., Honic et al., 2019).

By utilising pre-defined elements and a modelling guide, the model of the building is developed in BIM. The BIM model is then checked for errors via a control tool, which also tests whether pre-defined elements have been used or not. This BIM -model contains geometric data of elements and their materials. The model is then exported to the material inventory and analysis tool. The predefined elements in the tool are assigned with LCA-data and Recyclability data from the eco-inventory database. As pre-defined elements in the BIM-Model are matched with those of the analysis tool, they have the same nomenclature (designation). Finally, the material passport results in the total material composition of the building, recycling potential, and environmental impact (M., Honic et al., 2019).

Madaster: A similar workflow can be observed with the Madaster Platform. The platform primarily uses IFC (Industry Foundation Classes) file as its source file, which includes geometric properties of the building elements, description of materials and classification (Madaster, 2021a). The IFC file can be exported from BIM software such as Revit etc. The source files are automatically checked for their completeness while being imported to the platform. Upon successful import, the platform will automatically match/link the elements present in the source file with the materials registered in the database. The elements can be linked manually as well. Once this is complete, this active data set is the latest version of material passport which can be downloaded in Excel or PDF formats. This is also the basis for the building's residual and circular value in Madaster Platform (Madaster, 2021b).

Madaster provides different roles and rights to different types of users. The three types of users are Admins, Manager and Reader. The admin is the owner of the account that contains material data related to one or more projects. The admin can delete, manage, modify and view the data in the platform. The admin enables the manager role to manage the data related to a particular project. The reader can view the data related to the projects (Madaster, 2021a). However, these users belong to a single firm or company. The interoperability, information access and information exchange between different stakeholders cannot be seen.

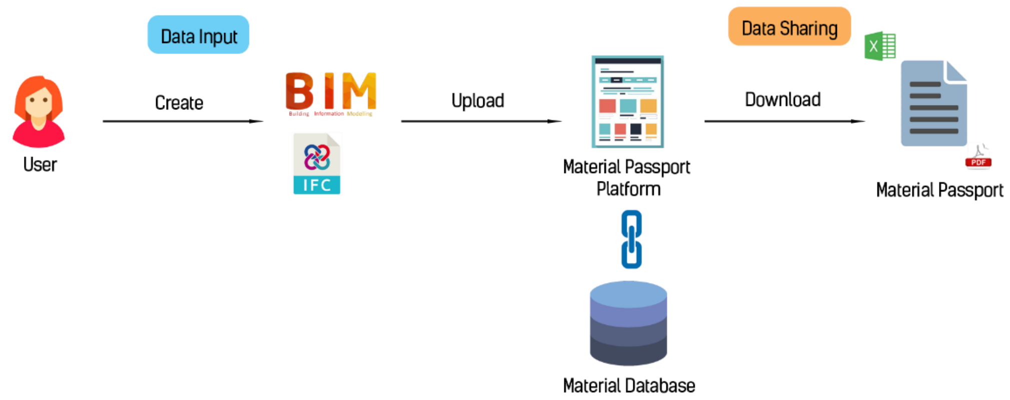


Figure 42:Scenario A: Work Flow of a BIM-based Material Passport

Example: 'de Orb' is a steel-framed structure designed by ABC architects. As there will be numerous components and materials involved in 'de Orb', let's focus on one component, i.e., structural steel columns, for better understanding. As shown in figure 37, the designer will create a detailed design of 'de Orb'. Upon completing the detailed design, the designer will upload the BIM model to the material passport platform to obtain the material passport for 'de Orb'. The BIM model will have Unique IDs for each BIM element. Hence the steel columns will also have this unique ID. This will help match the pre-defined steel column from the BIM model with the material data from the material database. Finally, this will result in a material passport comprising the total steel composition of the building, its recycling potential, and environmental impact. This material passport can be downloaded by the designer as a PDF or an Excel file and shared with relevant stakeholders (usually clients).

4.1.2. Scenario B: Hyperledger Fabric-based Material Passport

The Hyperledger Fabric-based Material passport is proposed to ensure the stakeholders' security, privacy, and confidentiality of data. The Hyperledger Fabric's Membership service provider is a tool for identity management for authorisation and authentication of Material passport entities. It creates and distributes digital certificates that contain a unique ID and information about users' access rights. The user uses these certificates to sign transactions and gain access to blockchain resources. The access rights and legitimacy of the stakeholders in the blockchain network can be verified with the help of these digitally signed transactions. To architect HLF, members belonging to different stakeholders such as suppliers, contractors, clients, designers etc., are made as endorsers, committers and orderers to ensure trustful, secure and smooth business operations.

The BIM objects will not be matched or linked with the material data from any material databases in this scenario. Instead, the respective manufacturers or suppliers of the building components/materials will provide the respective information relating to products and materials. For instance, let us assume that the Manufacturer/supplier has to upload the material properties data to the material passport. Let us look at the transaction flow:

1. The manufacturer/ supplier enters the material properties into the blockchain network via the Material Passport application . This data is encrypted with the private key of the manufacturer and digitally signed by him. This proposal is sent to different endorsers (in this case, client, designer, contractor, advisor) for receiving endorsements.

2. Before executing the transaction, the endorsing peers (such as client, contractor, designer etc.) inspect the transaction proposal received from the Manufacturer's application to check for its provenance, access rights and format. Upon completion, the transaction is simulated by executing the chain code to identify the read or write sets during the execution. Then the endorser digitally signs the proposal using his certificate and sends it to the client in the form of endorsement.

3. The Manufacturer's application will receive the endorsed transaction proposal from all the endorsers. After this, the client inspects the read-write sets of the endorsements to ensure that all the endorsements he received have the same result. Later, the client sends these endorsed transaction proposals to the ordering service, where they get packed into blocks, which are then broadcasted to the committer nodes in the network for validation.

4. The committer peers authenticate the transaction owner (in this case, the manufacturer) before the transaction is validated. The validation occurs in three stages. In the first stage, the read and write sets are compared to the world state of the ledger to make sure that the data has not been altered since the transaction was endorsed. In the second stage, the transaction will be deemed invalid if it does not comply with the endorsement policy of the network. In the third stage, the block is appended to the chain and the transaction will be marked invalid (if it does not satisfy the first or second stage) in the block's transaction record. In the last stage, the transaction

owner (manufacturer) and concerned parties are notified regarding the transaction result.

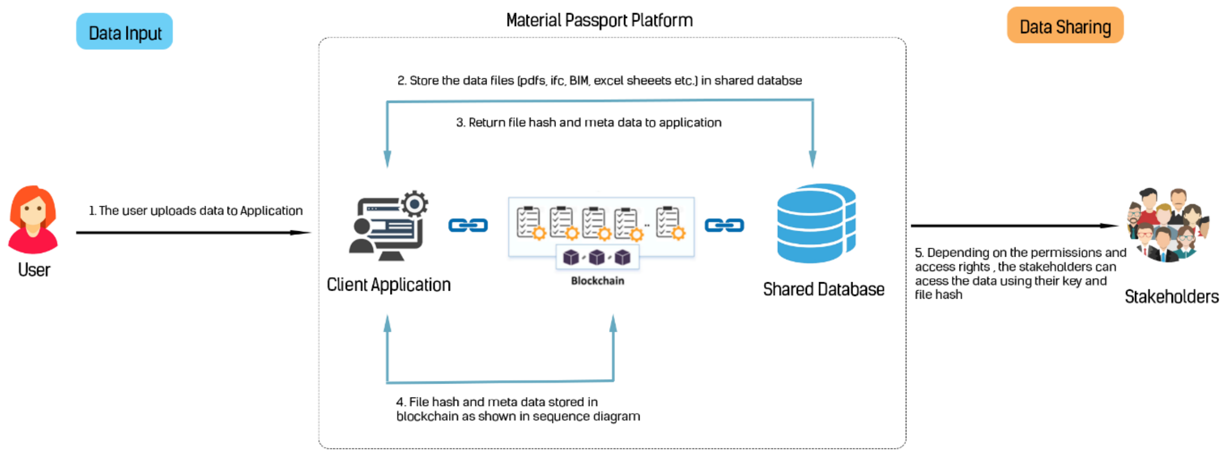


Figure 43: Scenario B: Workflow of Hyperledger Fabric-based Material Passport

In the case of de Orb, the manufacturer of the steel column will provide information regarding the material properties of the column, such as lifespan, specifications, certification, composition and material toxicity. The data transaction takes place as described above and as shown in figure 38 above. However, suppose the documents (drawings, BIM files, BoQs, Certificates etc.) are uploaded to the material passport application. In that case, they will be stored in the shared database anchored to the blockchain network, whereas the file hash will be recorded on the blockchain. There are various stakeholders involved in this project like client, contractor, designers, manufacturers etc. These stakeholders formulate a policy to manage the Hyperledger Fabric-based Material passport before deploying the network. These policies decide the roles of various stakeholders, such as which one has access to read and(or) write data onto a material passport. Based on the policy, the access rights of the users are automated by Membership Service Provider and Certificate authority. For example, the access rights of the designer allow him to view the data provided by the steel column's manufacturer and based on this data, the designer designs the structural steel frame for 'de Orb'. This procedure is carried out for other building components and materials too. Similarly, in the construction phase, the contractor enters the as-built data, and during the use phase, the facility manager enters maintenance related data. During the end-of-life or reuse phase, the urban miners or recyclers will have access to entire data related to the materials used in the building, which will assist them in taking decisions regarding reuse or recycling etc.

4.1.3 Analysis of Scenarios

Scenario A: BIM-based Material Passport and Scenario B: Hyperledger Fabric-based Material Passport is analysed based on the elements of material passport such as provision, storage, access and quality of information (Damen, 2012). The BIM-based material passport (Scenario A) is simple to develop when compared to Hyperledger Fabric-based material passport. However, there are various barriers present in BIM-based material passports that are hindering its application. Some of these barriers are classified into different elements of material passport and are listed below:

- **Provision of Information:** To carry out Life-cycle assessment, health risk assessments etc., detailed information related to materials (Intellectual property) is required. But the manufacturers are reluctant to share the material data as they fear losing competitive advantage in the market and compromising their commercial status (Debacker and Manshoven, 2016; Miu, 2020).

- **Storage of Information:** The other barrier is the ownership rights of the data. In the current system, the database owner will be the owner of the data (Kedir et al., 2021; Rudolphi, 2018). For example, the manufacturer shares the material data with the designer. The designer designs the building based on this data and uploads the BIM file to the Material Passport platform to generate the passport. In this case, the designer will become the owner of the material passport even though most of the material related data is provided by the manufacturer.

- **Access to Information:** Every actor cannot be given complete access to all the data present on the material passport. For example, in the BIM-based material passport platform such as Madaster, the actor with just view access can still view all the details present in the material passport. Therefore, it is important to have different access levels to see different data to have data privacy.

- **Quality of Information:** The existing material passport system lacks Data validation and credibility of the data that is being shared (BAMB, 2017). Additionally, the lack of a standard for material passports affects the quality of information that is being shared. Further, new products and materials are being introduced in the market constantly. Thus, the material databases might not be up-to-date, leading to an information gap (BAMB, 2017).

Apart from the barriers mentioned above, the other drawback of the BIM-based material passport is that it is mainly focused on and is the result of the design stage of the building. Hence, As-built data during the construction phase and Maintenance data during the Use phase of the building may not be updated (BAMB, 2017). Therefore, the actual residual value and circular value of the components and materials cannot be calculated at the End-of-Life phase. This makes the material passport a static document.

The Hyperledger fabric-based Material Passport (Scenario B) is developed mainly to address the barriers of BIM-based material passports. However, not all the barriers of material passports can be addressed by implementing blockchain technology. The newly proposed Hyperledger Fabric-based Material Passport framework can address the barriers as discussed below:

Provision of Information: Since the data is being provided to the material passports, the respective data hash will be stored in the blockchain. This makes it transparent and traceable on who has uploaded what data. However, the different actors have different access rights. Hence, the actors can share information to the material passport without any reluctance.

Storage of Information: Every actor participating in the network is responsible for the data they provide and will remain the owner of their data. However, the data and the document hash are stored while the documents are stored in the shared database. This is to ensure that the provided data and documents are not visible to all the participants in the network. The added advantage of adopting this step is that it reduces the payload of the network, thereby increasing the network latency. Once the hash is validated and appended to the ledger, it becomes difficult to modify data and documents as it can be detected by checking if the data hash is still matching (Morabito, 2017).

Access to information: To protect the confidentiality of the sensitive information provided to material passports, it is essential to have predefined user access rights that only specific data is visible to them. These rights can be managed via a Membership service provider (MSP), Certificate Authority and Access Control List (ACLs) of the Hyperledger Fabric, making it unique. For example, the manufacturer provides the material data to the material passport. But the designer has only access limited to data necessary for carrying out the design and assessments.

Quality of Information: One of the most critical aspects of materials passport is the quality of the information that is being provided. As mentioned earlier, the transparent nature of the blockchain network allows its participants to trace who has provided the data, and this data can be viewed and verified by the participants who have access rights. These features of blockchain facilitate a form of social control within the network to provide quality information (Morabito, 2017).

The Hyperledger fabric-based Material passport is dynamic as material data is updated to the material passport throughout the lifecycle of the building. This provides an opportunity to calculate the actual residual value, and the circular value of the components and materials cannot be calculated at the End-of-Life phase. Hyperledger Fabric-based Material passport is proposed to ensure security, privacy and confidentiality of data among the stakeholders. Hyperledger fabric protects the confidential and sensitive information provided to material passports via its Membership service provider, Certificate Authority and access control list, which defines access rights to users. However, in HLF's Material passport, their respective manufacturers or suppliers will provide the information related to products and materials. This will ensure that the latest data is available and eliminate the use of a material database. However, there are certain drawbacks in adopting this framework as there are no adequate proven use cases. Lack of skilled programmers to develop such a system in the construction industry. The construction industry has minimal knowledge and awareness regarding blockchain technology.

4.2 Validation

The process to elicit information from the interviewer from another person through verbal interchanges is known as an interview (Dunn, 2005). Individual interviews were conducted in this research to validate the barriers of material passports and proposed Hyperledger fabric-based material passport framework. Longhurst (2003) states that there are three types of interviews: Structured, Semi-structured and Open interviews. The structured interview is guided with a set of standard questions that are predetermined and are asked in the same order in every interview. On the other hand, in an open interview, the interview is guided by the interviewee than a set of predetermined questions. The semi-structured interviews lie right in between these two types of interviews. This type of interview has a predetermined order to a certain extent but is flexible depending on the answers given by the interviewee.

For this research, a semi-structured method of interviewing was adopted as it has the flexibility to deviate from the predetermined list of questions. This flexibility stimulates room for discussion and brings us new ideas and concepts during the interviewees. However, a list of predetermined questions was asked in order to cover the main topics and validate the barriers of material passports and the Hyperledger Fabric-based Material passport's framework. The most crucial part of the interview is choosing its participants (Cameron, 2005). For this research, the participants were chosen based on their job role, experience and knowledge they possess related to my research topic. The other main criteria for selecting the participants was their or their company's position as a stakeholder in the built environment sector. This method of choosing participants is known as purposive sampling (Baarda et al., 2005). Table 9 lists the various participants that participated in the interview process.

The interviews were conducted virtually via online meeting platforms such as Microsoft Teams or Zoom due to the pandemic. The interviews were recorded in order to preserve the quality of the data during its analysis. The interviewee's consent was taken before the start of the interview recording. These recordings were stored on a secure TU Delft cloud server. Upon completion of the interviews, the recordings were transcribed into a document. For analysing the transcribed data, the most effective and common- Thematic Analysis method was adopted (Clarke and Braun, 2014; Canary, 2019). First, the transcripts were read very carefully to identify similar themes and to get important insights. Next, the data was conceptualised and segmented under different themes identified earlier. This is done mainly to condense the transcribed data. Based on this, the findings from the interviews were incorporated in the following sections.

Table 10: Stakeholders Interviewed

Stakeholder	Role	Company
Architect 1	Design Leader	Strukton Worksphere
Architect 2	Consultant	Copper8
Advisor	Consultant	Alba Concepts
Client	Innovation Manager	Province Noord-Holland
Urban Miner	Project coordinator	New Horizon Urban Mining BV
Blockchain and Material Passport Developer	Chief Technical Officer	Excess Materials Exchange

4.2 Validation: Material Passport

4.3.1 Architect 1

According to the architect, it is essential to know the decomposition of a building. He also mentioned that it is important for a designer to have a good understanding of building as a whole and its parts. This can be achieved through the use of material passports. The architect's firm does not directly use material passports. However, they advise their clients to use material passports (*Madaster or a BIM-based model as a solution)*. The architect also mentioned that during his time at firm de Architekten Cie., they developed a material passport LLMNT in collaboration with ABN Amro for the CIRCL pavilion. Besides the barriers mentioned in the literature, the architect mentioned that the building must be decomposed to its parts (doors, floors, windows etc.) correctly else linking the information would not be possible to those parts.

4.3.2 Architect 2 (Consultant)

The consultant believes in the future use of the material passport as it helps to provide an insight into the materials used in the building. This information is crucial for the future re-use of these materials. However, the consultant's company does not use material passports themselves as they do not construct anything; they advise their clients (Provincie Noord-Holland) to use material passports. However, this is not something that is embedded into their process since most of the material projects are made as pilot projects where the organisation is not sure about using a material passport.

The consultant agreed to the barriers that were identified through the literature. Furthermore, he emphasised on Lack of standards for a material passport as the most critical one because the phenomenon of material passport is not clear. This leads to excess consumption of time and money, which will make it difficult for the organisations to invest. He suggests that the Government of the Netherlands standardise the passports as it will become much easier for broader implementation.

4.3.3 Advisor

The advisor's firm specialises in Built Environment, focuses mainly on circularity and sustainability. They manage projects from design to use phase of a building and advice their clients on how they can reach their goal of circularity and sustainability within their real estate. As a firm, they use material passports to calculate Building Circularity Index. In addition to this, they advise their clients to use material passports to facilitate the reuse of materials. The advisor believes it is important to use material passports through the use phase, facilitating an efficient maintenance process and transparent flow of material data which is significant for the reuse of materials.

The advisor agreed with all the barriers mentioned related to material passports. In addition to this, she mentioned some important barriers that have to be considered, such as the level of detail of the materials, which she thinks is confusing when one looks at different platforms available in the market. In addition to this, she suggested that people working in the industry have to change their attitude to move forward and try new things.

4.3.4 Client

The client thinks that material passports are a valuable tool to solve coordination problems in supply chains related to the material flow and allocating the materials back to the concerned parties in the value chain. He believes that material passports provide a digital footprint of a product that provides information to different parties to reuse materials and think about a circular solution. The client agreed with all the barriers that were identified. In fact, he explained why he thinks it is a barrier which can be found in the appendix. In addition to this, he found integrating the material passport with the business process as a barrier. Furthermore, he said that the material passports' usability had not been proven, and for it to add value in the industry, it needs to be useful. The client believes making the data in the material passport more dynamic by linking it with other systems like BIM and Digital twins will add value.

4.3.5 Urban Miner

In the urban miner's firm, the material passport is used to inventory the elements, building products and materials present, including their properties during the reuse phase. The urban miner agreed to the barriers related to a material passport that were identified in this study. Furthermore, he mentioned the reliability of the data as a crucial barrier. He mentions a Government policy on material passports and a Global standard as a requirement to facilitate the implementation of material passports on a broader scale.

4.3.6. Blockchain and Material Passport Developer

The Material Passport Developer says that many materials are not registered digitally. Hence, these products lie in warehouses as they can't be tracked. This lack of digital registration means that information regarding the location, quantity, volume and condition is not available. With the application of Material passports, the developer believes that the required information can be captured and stored. He also suggested that information from material passports can be used for predictive analytics to reduce waste and increase the circular use of materials.

The developer agreed to the barriers related to material passports that were mentioned. Besides, he stated interoperability as a major barrier because different material passports have different nomenclatures and data models and do not have uniform data structures. The developer also stated that it is essential to exchange information in a secure and private way.

4.4 Validation: Hyperledger Fabric-based Material Passport Framework

The majority of the interviewees agreed that blockchain could be the possible solution to help stimulate the use of material passports. However, the architect and the client think that blockchain will be a technical solution to material passports. Since a material passport is more like a shared database with multiple stakeholders providing the data, it requires a tamperproof log and predefined access rights for users to protect the confidential data in the material passport; he thinks Hyperledger Fabric is a good fit. The advisor complements this framework as an intelligent and innovative solution as it helps save data in the right way. Furthermore, the client thinks blockchain can be the solution to this problem as it solves the ownership issues, create different layers of accessibility, makes data traceable and hence it is transparent and most importantly, the concept of validation makes the technology unique. Moreover, Hyperledger Fabric might solve the scalability and unsustainable consensus mechanism issues of traditional blockchain. The material passport developer thinks that a Hyperledger fabric-based material passport can be a good use case. He compliments the use of shared databases and anchoring it to the blockchain. During the interviews, the interviewees were asked to map the barriers related to material passports with the aspects of Hyperledger fabric. The main aim of this was to get an insight into which aspects of Hyperledger fabric are useful to overcome the barriers related to material passports. The consolidated result of this is shown in Figure 38.

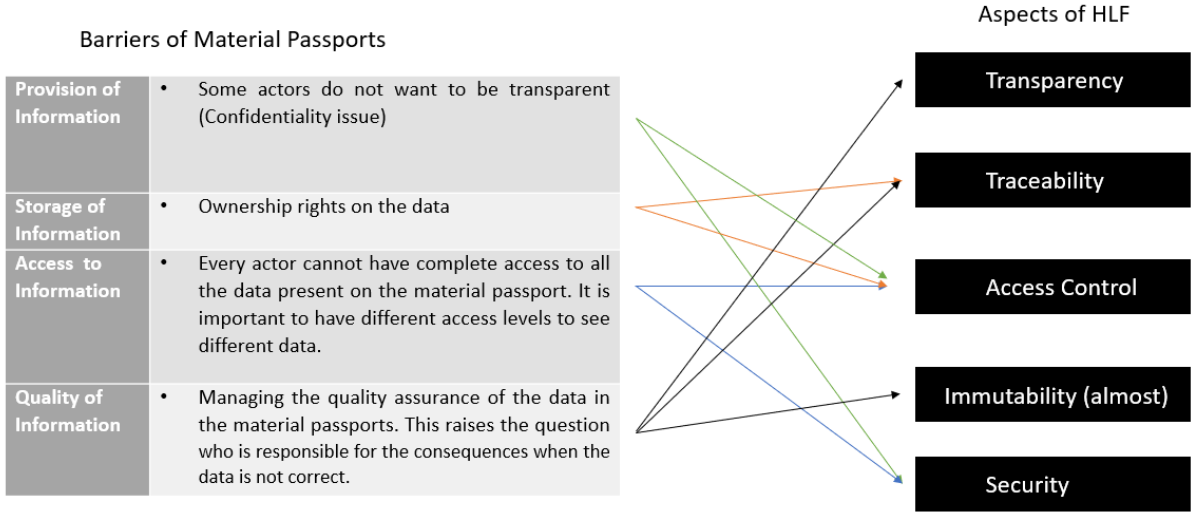


Figure 44:Mapping barriers of material passports with aspects of HLF

No matter how intelligent or innovative the solution is, it has its disadvantages, says the advisor. The architect says that the organisations need to organise their business process around these material passports besides adopting blockchain technology. This would hinder the process of implementing material passports. Also, there is a splint incentive as the passport makers have to invest time and money in the passport, while the benefits of the passport are more in the long term. On the other hand, the client believes the lack of a standard for a material passport is still a crucial barrier even to developing a prototype. Additionally, the advisor thinks that the attitude among the practitioners in the industry should change to try cross-discipline collaboration to provide innovative solutions to industry-oriented problems. This was backed by a material passport developer as well as he thinks that the majority of the experts in the industry lack the awareness and understanding about blockchain technology. The other barrier he mentioned was finding interested parties and bringing them together before setting up the network.

4.4 Conclusion

Scenario A: BIM-based Material Passport and Scenario B: Hyperledger Fabric-based Material Passport is analysed based on the elements of material passport such as provision, storage, access and quality of information (Damen, 2012). This step was carried out to see whether the proposed Blockchain-based Material Passport framework will address the barriers of BIM-based material passports. The analysis of scenarios showed that the Hyperledger Fabric-based Material Passport has a significant advantage over the BIM-based material passports and can address its barriers regarding the provision, storage, access, and quality of information.

Further, the interviews were conducted to validate the material passports and proposed Hyperledger fabric-based material passport framework. Initially, all the interviewees had agreed with the barriers that were identified related to material passports. However, additional barriers were shared by the interviewees that were relevant to material passports. These barriers are an unclear level of detail of building components and materials and incorrect decomposition of the building. Later, the interviewees revealed their thoughts regarding the proposed framework and thought it might overcome most of the barriers related to material passports identified in this study. Furthermore, they were critical about the new technology being adopted in the industry. The interviewees found added value by adopting blockchain technology for material passports. Due to the explorative nature of this research, the outcome cannot be generalised for all the cases. However, they can be a stepping-stone for adopting innovative technologies as blockchain technology in the built environment sector.

5 Discussion & Conclusion

5.1 Discussion

Take-make-dispose is the current Linear economy's model. This paradigm is based on the consumption of resources rather than the preservation of their value. If this model remains dominant, it will lead to material scarcity, thereby increasing materials prices. The linear economy also has a negative impact on the environment as it creates large amounts of waste. The circular economy's concept is to minimise waste, maximise value and facilitate the reuse of materials. This research was carried out to elevate digital innovation in the circular built environment. However, a transition toward a circular economy has its barriers, and one of the most important ones was the lack of exchange of information among stakeholders. A tool called material passport was developed to overcome this gap and facilitate the transition towards the circular economy in the built environment sector. Through literature, it was found that many barriers exist even though material passports were developed to facilitate information sharing. Analysing these barriers and proposing a solution that can influence the implementation of material passports on a broader scale is the foundation of this thesis.

The research objective and the questions were formulated to reflect the potential of blockchain technology in influencing the implementation of material passports. The concepts of blockchain and material passports are relatively new. However, the features of blockchain were promising to overcome the barriers of material passports and fulfil its requirements. Although the traditional blockchain was promising, it had many challenges that were not in line with Circular Economy principles and requirements for a business process. To provide a solution to overcome the barriers the traditional blockchain poses and without hampering its features, Hyperledger Fabric, a private permission blockchain, was adopted to develop a framework for material passports.

The use and barriers of material passports and the proposed framework were validated by developing Scenario A: BIM-based Material Passport and Scenario B: Hyperledger Fabric-based Material Passport and analysing them with aspects of material passports such as provision, storage, access and quality of information. Further, the validation was carried out by conducting semi-structured interviews with experts from the industry. The interviewees belonged to different stakeholders groups involved during the lifecycle of a building. This step was performed to determine whether the research offers any added value.

Blockchain is still a developing technology and hence can be termed immature. The parties benefiting by implementing blockchain have exaggerated the advantages of the technology. This has created a vast 'hype' leading to misconceptions regarding the technology. Often, blockchain is seen as a remedy for all issues. However, the benefits of the technology must be weighed with the time and costs of implementing and maintaining to determine the actual benefit that this technology provides.

5.2 Limitations

In this section, the limitation of this research have been discussed, which need to be taken into consideration:

- The research was conducted as part of academics in the Master's program. Hence there was a time constraint. Due to the time constraints, the scope of the research had to be limited, hence only one type of blockchain was analysed, i.e. Hyperledger Fabric (a private permissioned blockchain).

- Limited availability of scientific literature and use cases on material passports made it difficult during the literature review and analysis. Even though there are several material passports available in the market like BAMB, Madaster, EME's Resource Passports, ABN AMRO's LLMNT passport, they are functionally and structurally different from each other. Hence, only one type of passport (ABN AMRO's LLMNT passport) was chosen for further research, analysis and development of the framework

- The Hyperledger fabric-based material passport framework was developed by a single researcher. If the framework was developed by a group of researchers or/and in collaboration with an organisation, it would have opened doors to many other factors and parameters that needed to be considered.

- As the research focused on developing a framework for material passports based on Hyperledger Fabric, industry practitioners with experience in material passports and knowledge in blockchain or vice versa were required for validation. Since material passports and blockchain technology are from two different disciplines, finding practitioners with these requirements was challenging, and only six validation interviews were conducted. However, the results from the interviews turned out to be more superficial than expected because not all the interviewees could answer all the questions.

5.3 Conclusion

The conclusion of this research is presented in the form of answers to sub-research questions and the main research question.

S1: What is a circular economy, and what is its influence on the built environment?

The circular economy concept is gaining momentum among practitioners, researchers, businesses and thought leaders due to the current emphasis on the scarcity of resources in addition to the increasing demand for raw materials, ultimately resulting in high prices of raw materials. The circular economy is a comprehensive and creative approach to a possible future economy, but there is no clear definition. According to Ellen McArthur Foundation, the circular economy concept is based on various schools of thought regarding sustainability, and they have had all influences in the birth of this concept. Circular Economy is an economic system that prioritises the aspects 'Reduce', Recuse, Recycle and Recovery of materials

"*The circular economy is an economy that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times*" (Ellen MacArthur Foundation, 2015, p. 5)

The high concentration of data, resources, capital, and talent in cities puts them in a unique place to stimulate the transition towards a circular economy. With such resources within such a small geographical area, reverse logistics and material collection would be more feasible. This stimulates abundant chances for reuse and collection based business models. As a result of the Circular economy, the construction industry will undergo significant changes. One such example is the concept of 'buildings as material banks,' which fundamentally alters how material flows must be handled. This concept shines the light on retaining the value of building materials and products at all times by maintaining, keeping and restoring them. This stimulates less usage of virgin materials and minimal waste production

S2: What are material passports, and how can they support the circular economy?

Material passports are tools designed to address the barriers of the Circular economy, such as lack of information sharing and materials exchange system. Material passports are intended to track the value of materials throughout their life cycle and introduce the residual value into the secondary market. Material passport will hold the key to this as it will contain information relevant to the different lifecycle stages of the building. Over time, a couple of instruments have been developed to facilitate materials and information exchange but are being operated on a smaller scale. A material passport keeps track of the different materials used in the building or components of the building, and how many of them are there. This information is recorded and transferred to different actors involved in other lifecycle stages of the building.

S3: What are the major barriers related to information sharing in a material passport?

Provision of Information	• No incentive for providing the data • Non availability of the data • Some actors do not want to be transparent (Confidentiality issue)
Storage of Information	• Ownership rights on the data
Access to Information	• Every actor cannot have complete access to all the data present on the material passport. It is important to have different access levels to see different data.
Quality of Information	• Managing the quality assurance of the data in the material passports. This raises the question who is responsible for the consequences when the data is not correct. • No standard for a material passport
Presentation of Information	• Lack of uniformity/standard in the data within built environment.

S5: What is blockchain technology and its characteristics?

In essence, blockchain is a data structure - a kind of database - to which only digitally signed data can be added collectively by the peer-to-peer network (without a central party). However, this data must conform to certain conditions (rules), which are also verified collectively. For example, to the Bitcoin blockchain, we can add transaction data that, in simplified terms, contains such a message: "I, Bob, want to transfer half a bitcoin to Alice". The network collectively verifies that the signer of the transaction, Bob, has enough unissued bitcoins. If so, the transaction is accepted by the network by adding it to the blockchain. The blockchain thus contains the complete history of all transactions. From this, it can be deduced how many bitcoins everyone owns.

These transactions are grouped into blocks that are added collectively by the network to the back of the blockchain. The last block, therefore, contains the most recently processed transactions. So the blockchain has all processed transactions, from the very first to the very last. From the moment they are included in the blockchain, the transactions are nearly immutable and cannot be deleted. Many participants in the blockchain network own a local copy of the blockchain, which they keep up-to-date. We call them nodes. So everyone has the same version of the blockchain. This allows the technology to exchange data and guarantees that everyone has the same and most up-to-date information. Each block contains a timestamp that the network has collectively validated. We, therefore, know exactly when a transaction was recorded in the blockchain.

Blockchain makes intensive use of cryptography. This is the use of mathematical principles to protect data. Properties such as integrity and confidentiality of data can be guaranteed using cryptography. Of course, the use of cryptography does not automatically imply that everything is also 100% safe.

There is an essential difference between permissionless and permissioned blockchain networks. Permissionless blockchain networks are networks where everyone has equal rights, and in practice, they are often public and open. Examples include Bitcoin, Ethereum and Litecoin. Today, the main permissionless blockchain networks use Proof of Work (PoW) as a consensus mechanism, guaranteeing everyone works with the same blockchain version. However, PoW has the disadvantage of consuming an enormous amount of energy. In practice, permissioned blockchain networks are usually shielded. Around the network, there is then an access control layer that determines who has access to the blockchain network and especially who is allowed to do what. Are usually. They are usually a lot more energy-efficient and faster. Although the technology is seen as promising, it will still take several years before it reaches maturity. This implies that it takes a lot of effort, money and risks to make and keep blockchain applications operational. Nevertheless, this does not stop companies and governments from already experimenting with the technology.

S6: What type of blockchain technology has the potential to address barriers of applying material passports on a large scale?

Blockchain technology provides opportunities to enhance the application of material passports based on key features such as its distributive nature, transparency and traceability, immutability and security. However, there are several challenges that this novel technology has to overcome, namely, privacy and security issues, scalability, unsustainable consensus mechanism (computing power) and lack of governance. These challenges hinder the application of blockchain in a business case (Davies, 2020). According to Davies (2020), a blockchain expert has specific requirements from a blockchain network from a business point of view:

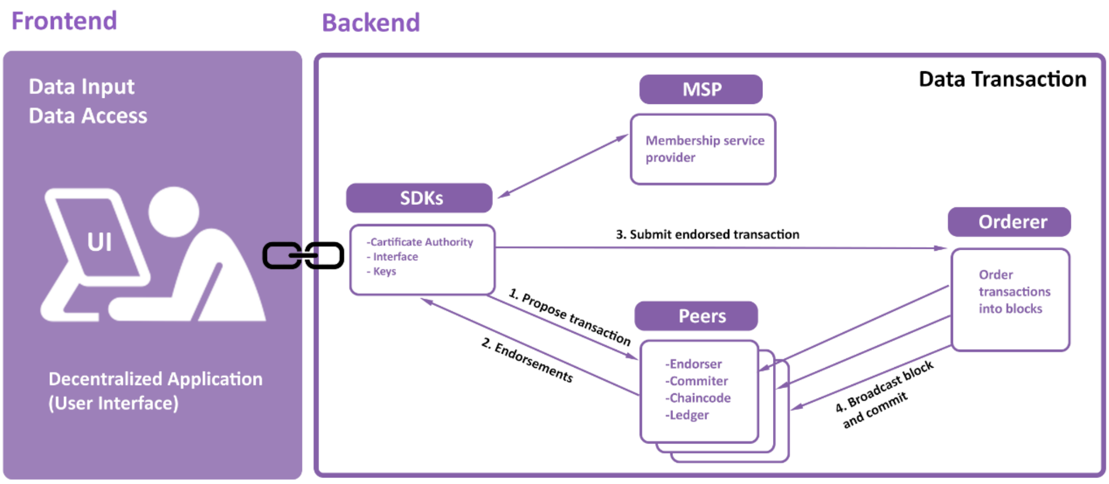
- The consortium requires a blockchain that allows them to govern who enters the network and the ability to confirm a new user's identity. (Aghimien, Aigbavboa, Oke, & Koloko, 2020)
- Swift transactions and scalability is a requirement for enterprises
- The consortium must pre-define the access control list for the exchange of sensitive data
- A resilient network

Davies (2020) believes that Hyperledger Fabric addresses the issues of a traditional blockchain and meets the enterprise requirements. Hyperledger Fabric (HLF) is an open-source private blockchain-based platform developed by the Linux Foundation. The Hyperledger encourages a collaborative approach to develop blockchain technologies via community process. HLF's architecture aims at the several challenging aspects of blockchain, such as scalability, flexibility, resilience and confidentiality.

S7: How to develop a blockchain-based material passport to address material passport's barriers and facilitate the circular built environment?

For developing a material passport, Hyperledger Fabric-based framework is proposed in this study to ensure security, privacy and confidentiality among the stakeholders who use the material passport. To develop a comprehensive system like Hyperledger Fabric-based Material Passports, software developers are required. Hence the framework developed in this thesis aims to be useful to develop Hyperledger Fabric-based Material Passport by Material Passport Developers. This framework will also help the stakeholders in the built environment to understand the information flow within the Hyperledger Fabric-based Material Passport.

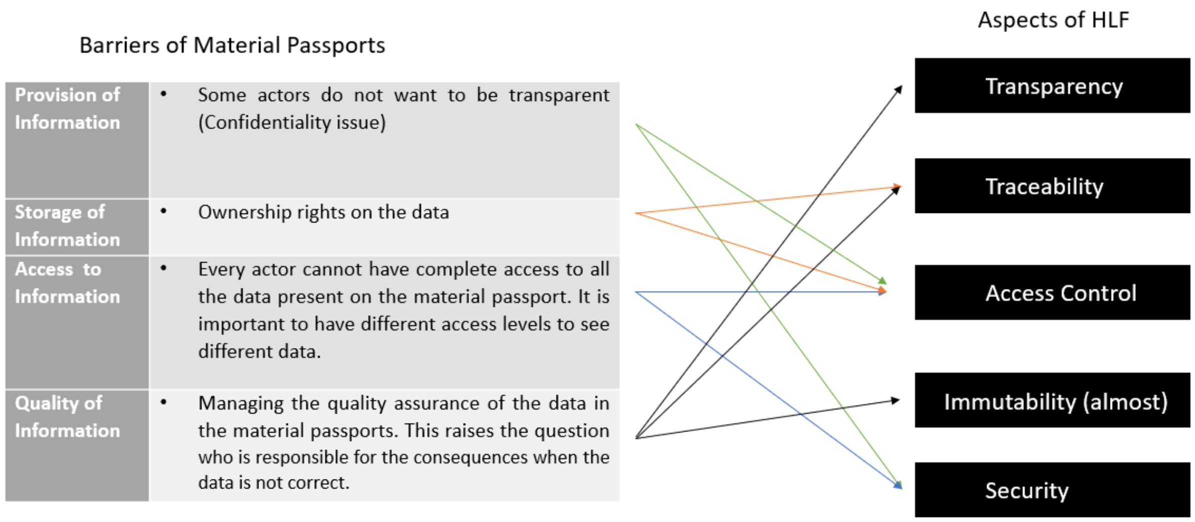
The proposed framework, as shown in the figure below and is divided into two parts, namely Front-end and Back-end. The front-end is what a user can see on the screen and interact with, or simply put, the Graphical User Interface (GUI). On the other hand, the application process that is not visible to the user such as, data processing, data storage, data transaction mechanism, etc. is known as Back-end.



S8: What are the implications of adopting blockchain-based material passports? What are the perspectives of industry practitioners on the current material passport and the blockchain-based material passport?

The Hyperledger fabric-based Material passport is dynamic as material data is updated to the material passport throughout the lifecycle of the building. This provides an opportunity to calculate the actual residual value, and the circular value of the components and materials cannot be calculated at the End-of-Life phase. Hyperledger Fabric-based Material passport is proposed to ensure security, privacy and confidentiality of data among the stakeholders. Hyperledger fabric protects the confidential and sensitive information provided to material passports via its Membership service provider, Certificate Authority and access control list, which defines access rights to users. However, in HLF's Material passport, their respective manufacturers or suppliers will provide the information related to products and materials. This will ensure that the latest data is available and eliminate the use of a material database. However, there are certain drawbacks in adopting this framework as there are no adequate proven use cases. Lack of skilled programmers to develop such a system in the construction industry. The construction industry has minimal knowledge and awareness regarding blockchain technology.

The majority of the interviewees agreed that blockchain could be the possible solution to help stimulate the use of material passports. However, the architect and the client think that blockchain will be a technical solution to material passports. Since a material passport is more like a shared database with multiple stakeholders providing the data, it requires a tamperproof log and predefined access rights for users to protect the confidential data in the material passport; he thinks Hyperledger Fabric is a good fit. The advisor complements this framework as an intelligent and innovative solution as it helps save data in the right way. Furthermore, the client thinks blockchain can solve this problem as it solves the ownership issues, creates different layers of accessibility, makes data traceable, is transparent, and most importantly, the concept of validation makes the technology unique. Moreover, Hyperledger Fabric might solve the scalability and unsustainable consensus mechanism issues of traditional blockchain. The material passport developer thinks that a Hyperledger fabric-based material passport can be a good use case. He compliments the use of shared databases and anchoring it to the blockchain. During the interviews, the interviewees were asked to map the barriers related to material passports with the aspects of Hyperledger fabric.



The architect says that the organisations need to organise their business process around these material passports besides adopting blockchain technology. This would hinder the process of implementing material passports. Also, there is a splint incentive as the passport makers have to invest time and money in the passport, while the benefits of the passport are more in the long term. On the other hand, the client believes the lack of a standard for a material passport is still a crucial barrier to developing a prototype. Additionally, the advisor thinks that the industry practitioners' attitude should change to try cross-discipline collaboration to provide innovative solutions to industry-oriented problems. This was backed by a material passport developer as well as he thinks that the majority of the experts in the industry lack the awareness and understanding about blockchain technology.

MQ: How can Hyperledger Fabric influence the application of material passports in the Circular built environment?

The Hyperledger fabric-based material passport framework was developed mainly to address the barriers of material passports and those of traditional blockchain. However, not all the barriers of material passports can be addressed with blockchain technology. This section describes how the newly proposed conceptual framework of private-permissioned blockchain can improve material passports.

Provision of Information: Since the data is being provided to the material passports, the respective data hash will be stored in the blockchain. This makes it transparent and traceable on who has uploaded what data. However, the different actors have different access rights. Hence, the actors can share information to the material passport without any reluctance.

Storage of Information: Every actor participating in the network is responsible for the data they provide and will remain the owner of their data. However, the data and the document hash is stored in while the documents are stored in the shared database. This is to ensure that the provided data and documents are not visible to all the participants in the network. The added advantage of adopting this step is that it reduces the payload of the network, thereby increasing the network latency. Once the hash is validated and appended to the ledger, it becomes difficult to modify data and documents as it can be detected by checking if the data hash is still matching (Morabito, 2017).

Access to information: To protect the confidentiality of the sensitive information provided to material passports, it is essential to have predefined access rights to users that only specific data is visible to them. These rights can be managed via a Membership service provider (MSP), Certificate Authority and Access Control List (ACLs) of the Hyperledger Fabric, making it unique. For example, the manufacturer provides the material data to the material passport. But the designer has only access limited to data that is necessary for carrying out the design and assessments.

Quality of Information: One of the most critical aspects of materials passport is the quality of the information that is being provided. As mentioned earlier, the transparent nature of the blockchain network allows its participants to trace who has provided the data, and this data can be viewed and verified by the participants who have access rights. These features of blockchain facilitate a form of social control within the network to provide quality information (Morabito, 2017).

In addition, the majority of the interviewees agreed that blockchain could be the possible solution to help stimulate material passports. However, the architect and the client think that blockchain will be a technical solution to material passports.

5.4 Recommendations for future work

This research is one of the first to develop a Blockchain-based conceptual framework for material passports. However, due to the explorative nature of this study and time constraints, everything could not be explained. Therefore, various recommendations for future research have been put forward.

- To develop a prototype for material passports based on this framework and test it.
- To explore other types of blockchain technologies to see if they can address the business needs.
- Focusing research on standardising a material passport
- To improve expert validation, conducting interviews with more stakeholders involved in the lifecycle of a building to gain deeper insight regarding the actual problem.
- Connecting material passports with other digital systems like digital twins and BIM to make it more dynamic

References

A. Davies (2020) *Pros and Cons of Hyperledger Fabric for Blockchain Networks.* DevTeam.Space; DTS. https://www.devteam.space/blog/pros-and-cons-of-Hyperledger-fabric-for-blockchain-networks/

ABN AMRO. (2017). *Prinsjesdagrapport 2017: De cirkel is rond*. 342.

Aghimien, D., Aigbavboa, C., Oke, A., & Koloko, N. (2020). Digitalisation in Construction Industry: Construction Professionals Perspective. *Proceedings of International Structural Engineering and Construction*, *5*(2). https://doi.org/10.14455/isec.res.2018.90

Ahsan, S., El-Hamalawi, A., Bouchlaghem, D., & Ahmad, S. (2007). Mobile technologies for improved collaboration on construction sites. *Architectural Engineering and Design Management*, *3*(4), 257–272. https://doi.org/10.1080/17452007.2007.9684647

Al-werikat, G. (2017). Simulating The Impact Of The Material Flow In The Jordanian Construction Supply Chain And Its Impact On Project Performance. *International Journal of Scientific & Technology Research*, *6*(3), 7–11.

Azhar, S., Jackson, A., & Sattineni, A. (2015). Construction apps: A critical review and analysis. *32nd International Symposium on Automation and Robotics in Construction and Mining: Connected to the Future, Proceedings*. https://doi.org/10.22260/isarc2015/0008

BAMB (2017). Framework for Materials Passport. https://www.bamb2020.eu/wp-content/uploads/2018/01/Framework-for-Materials-Passports-for-the-webb.pdf

Bauman, D., Lindblom, P., & Olsson, C. (2016). Blockchain Decentralized Trust. Stockholm: Entreprenörskaps Forum https://entreprenorskapsforum.se/wp-content/uploads/2016/10/NaPo_Blockchain_webb.pdf

Bos, R. (2021). Windows for Circularity: An analysis to identify circular interventions in the different stages of the design process of an office building, retrieved from http://resolver.tudelft.nl/uuid:3faf874e-da26-4421-9cbd-f84756d4dd6d

Bosch-Rekveldt, M. G. C. (2011). *Managing project complexity: A study into adapting early project phases to improve project performance in large engineering projects*.

Bowden, S., Dorr, A., Thorpe, T., & Anumba, C. (2006). Mobile ICT support for construction process improvement. *Automation in Construction*, *15*(5), 664–676. https://doi.org/10.1016/j.autcon.2005.08.004

Brenig, Christian; Schwarz, Jonas; and Rückeshäuser, Nadine, "VALUE OF DECENTRALIZED CONSENSUS SYSTEMS – EVALUATION FRAMEWORK" (2016). *Research Papers*. 75.

https://aisel.aisnet.org/ecis2016_rp/75

Bryson, J. M. (2004). What to do when stakeholders matter: Stakeholder Identificatixon and analysis techniques. *Public Management Review*, *6*(1), 21–53. https://doi.org/10.1080/14719030410001675722

Canary, A. (2019, October 10). How to Analyze Interview Transcripts in Qualitative Research. Rev; Rev.

https://www.rev.com/blog/analyze-interview-transcripts-in-qualitative-research

Chen, Y., & Kamara, J. M. (2011). A framework for using mobile computing for information management on construction sites. *Automation in Construction*, *20*(7), 776–788. https://doi.org/10.1016/j.autcon.2011.01.002

Chowdhury, M. J. M., Colman, A., Kabir, M. A., Han, J., & Sarda, P. (2018). *Blockchain Versus Database: A Critical Analysis. 2018 17th IEEE International Conference On Trust, Security And Privacy In Computing And Communications/ 12th IEEE International Conference On Big Data Science And Engineering (TrustCom/BigDataSE).*

Circular Dutch economy by 2050. (2016). Government of the Netherlands https://www.government.nl/topics/circular-economy/circular-dutch-economy-by-2050#:~:text=The%20government%2Dwide%20programme%20for,smarter%20and%20more%20efficient%20way.

Clarke V., Braun V. (2014) Thematic Analysis. In: Teo T. (eds) Encyclopedia of Critical Psychology. Springer, New York, NY. https://doi.org/10.1007/978-1-4614-5583-7_311

D. Puthal, N. Malik, S. P. Mohanty, E. Kougianos and G. Das, "Everything You Wanted to Know About the Blockchain: Its Promise, Components, Processes, and Problems," in IEEE Consumer Electronics Magazine, vol. 7, no. 4, pp. 6-14, July 2018, doi: 10.1109/MCE.2018.2816299.

de Architekten Cie (2017). Rapportage Materialenpaspoort. Amsterdam: ABN AMRO

de Bruijn, H. (2012). Management in Networks. In *Management in Networks*. https://doi.org/10.4324/9780203885666

De Bruijn, H., Heuvelhof, E. Ten, & Veld, R. In 'T. (2002). *Why Project Management Fails in Complex Decision Making Processes*.

Dyson, R. G. (2004). Strategic development and SWOT analysis at the University of Warwick. *European Journal of Operational Research*, *152*(3), 631–640. https://doi.org/10.1016/S0377-2217(03)00062-6

Ellen MacArthur Foundation (2013) Towards the Circular Economy vol.1. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

Ellen MacArthur Foundation. (2013). Towards a Circular Economy: Business Rationale for an Accelerated Transition. Ellen MacArthur Foundation

Ellen MacArthur Foundation. (2015). Growth whithin: A Circular Economy vision for a competitive Europe. McKinsey Center for Business and Environment.

Excess Materials Exchange. (2020). Excessmaterialsexchange.com. https://excessmaterialsexchange.com/en_us/news/resources-passports-circular-economy/

Excess Materials Exchange. (2021). Excessmaterialsexchange.com. https://excessmaterialsexchange.com/nl/

Fitriatun, E. (2019). 済無No Title No Title. *Journal of Chemical Information and Modeling*, *53*(9), 1689–1699. https://doi.org/10.1017/CBO9781107415324.004

Foundation, E. M. (2015). Towards a Circular Economy: Business Rationale for an Accelerated Transition. *Ellen MacArthur Foundation (EMF)*, 20.

GitHub. (2018). *Centralised vs. Decentralised vs. Distributed? · Issue #5 · dwyl/cid*. GitHub. https://github.com/dwyl/cid/issues/5

Goldstein, A. B., Sokolov, N. A., Elagin, V. S., Onufrienko, A. V., & Belozertsev, I. A. (2019). Network Characteristics of Blockchain Technology of on Board Communication. *2019 Systems of Signals Generating and Processing in the Field of on Board Communications, SOSG 2019*, 1–5. https://doi.org/10.1109/SOSG.2019.8706826

Green Deal Circulaire Gebouwen. (2016). Handleiding en paspoort circulaire gebouwen. 11. https://www.greendeals.nl/sites/default/files/2019-12/GD178%20Handleiding%20Circulaire%20gebouwen.pdf

Goossens, J., Verslype, K., & Tjong Tjin Tai, E. (2020). *Blockchain en smart contracts: Herijking van de rol van de vertrouwde tussenpersoon in de algoritmische samenleving.*

Gupta, S., & Sadoghi, M. (2019). Blockchain Transaction Processing. *Encyclopedia of Big Data Technologies*, 366–376. https://doi.org/10.1007/978-3-319-77525-8_333

Gupta, V., & Singh, A. K. (2018). Current Scenario of Public-Private Partnership (Ppp) Projects in India. *International Research Journal of Engineering and Technology*, 5–8.

Harty, C., & Collinge, W. (2009). *Improving information sharing across construction stakeholders: an organizational semiotics approach*. (October 2014), 348–357. Retrieved from http://centaur.reading.ac.uk/12084/

Hertogh, M., & Westerveld, E. (2010). Playing With Complexity. Management and Organisation of Large Infrastructure Projects. *World*, 377.

Hevner, A., March, S., Park, J., & Ram, S. (2004). Design Science in Information Systems Research. *MIS Quarterly*, *28*(1), 75. https://doi.org/10.2307/25148625

Hoezen, M., Reymen, I., & Dewulf, G. P. M. . (2006). The problem of communication in construction. *Communication*, *1*(1), 4.

Honic, M., Kovacic, I., & Rechberger, H. (2019). Concept for a BIM-based Material Passport for buildings. *IOP Conference Series: Earth and Environmental Science*, *225*, 012073. https://doi.org/10.1088/1755-1315/225/1/012073

Honic, M., Kovacic, I., & Rechberger, H. (2019). Improving the recycling potential of buildings through Material Passports (MP): An Austrian case study. *Journal of Cleaner Production*, *217*, 787–797. https://doi.org/10.1016/j.jclepro.2019.01.212

Hosseini, R., Chileshe, N., Zou, J., & Baroudi, B. (2013). Approaches of Implementing ICT Technologies within the Construction Industry. *Australasian Journal of Construction Economics and Building - Conference Series*, *1*(2), 1. https://doi.org/10.5130/ajceb-cs.v1i2.3161

Hua, Y. Y., Liu, A. M. M., & Chan, I. Y. . (2014). Culture Dynamics of Information and Communication Technology (ICT) Adoption in Construction Companies. *Engineerin Project Organisation Conference*, (May), 1–18.

Khelifi, A., & Hesham, K. (2016). A Mobile Device Software to Improve Construction Sites Communications "MoSIC." *International Journal of Advanced Computer Science and Applications*, *7*(11), 51–58. https://doi.org/10.14569/ijacsa.2016.071108

Kim, C., Park, T., Lim, H., & Kim, H. (2013). On-site construction management using mobile computing technology. *Automation in Construction*, *35*, 415–423. https://doi.org/10.1016/j.autcon.2013.05.027

Kormuťák, A., Čamek, V., Branná, M., Čelková, M., Vooková, B., Maňka, P., … Gömöry, D. (2013). Introgressive hybridization between Scots pine and mountain dwarf pine at two localities of northern Slovakia. *Folia Oecologica*, *40*(2), 201–205.

Kovacic, I., Honic, M., & Rechberger, H. (2018). Proof of Concept for a BIM-Based Material Passport. *Advances in Informatics and Computing in Civil and Construction Engineering*, 741–747. https://doi.org/10.1007/978-3-030-00220-6_89

Labazova, O., Dehling, T., & Sunyaev, A. (2019). From hype to reality: A taxonomy of blockchain applications. *Proceedings of the Annual Hawaii International Conference on System Sciences*, *2019-Janua*, 4555–4564. https://doi.org/10.24251/hicss.2019.552

Lee, S. H., Peña-Mora, F., & Park, M. (2006). Dynamic planning and control methodology for strategic and operational construction project management. *Automation in Construction*, *15*(1), 84–97. https://doi.org/10.1016/j.autcon.2005.02.008

LILLEY, D., LOFTHOUSE, V., & BHAMRA, T. (2005). *This item was submitted to Loughborough ' s Institutional Repository by the author and is made available under the following Creative Commons Licence*.

Madaster (2021a). Madaster User Manual: General user guide to Madaster Platform. https://docs.madaster.com/files/en/Madaster%20-%20User%20Manual.pdf

Madaster (2021b). Madaster Action Plan: Process description to create a materials passport in the Madaster Platform. https://docs.madaster.com/files/en/Madaster%20-%20Action%20Plan.pdf

Mahalingam, A. (2010). PPP experiences in indian cities: Barriers, enablers, and the way forward. *Journal of Construction Engineering and Management*, *136*(4), 419–429. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000130

Mak, S. (2001). A model of information management for construction using information technology. *Automation in Construction*, *10*(2), 257–263. https://doi.org/10.1016/S0926-5805(99)00035-7

Materials Passports - BAMB. (2019, February 28). BAMB. https://www.bamb2020.eu/topics/materials-passports/

Mesároš, P., & Mandičák, T. (2017). Impact of ICT on Performance of Construction Companies in Slovakia. *IOP Conference Series: Materials Science and Engineering*, *245*(7), 0–9. https://doi.org/10.1088/1757-899X/245/7/072044

Murray-Webster, R., & Simon, P. (2006). Making Sense of Stakeholder Mapping. *PM World Today*, *3*(11), 5. Retrieved from http://skat.ihmc.us/rid=1JGD4CJZ4-F9CF0Y-1KM6/SEMINAL stakeholder mapping in 3d.pdf

Ogunniye, G., Toniolo, A., & Oren, N. (2018). A dynamic model of trust in dialogues. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *10757 LNAI*(May), 211–226. https://doi.org/10.1007/978-3-319-75553-3_15

Olivia, M., & Nikraz, H. (2012). Properties of fly ash geopolymer concrete designed by Taguchi method. *Materials and Design*, *36*, 191–198. https://doi.org/10.1016/j.matdes.2011.10.036

Paudyal, G. (2012). Role of ICT in construction. *Education Scottland*, (August 2016), 2–5. Retrieved from http://www.educationscotland.gov.uk

Pea-Mora, F., Chen, A. Y., Aziz, Z., Soibelman, L., Liu, L. Y., El-Rayes, K., … Mathur, S. (2010). Mobile ad hoc network-enabled collaboration framework supporting civil engineering emergency response operations. *Journal of Computing in Civil Engineering*, *24*(3), 302–312. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000033

Peffers, K., Tuunanen, T., Gengler, C. E., Rossi, M., Hui, W., Virtanen, V., & Bragge, J. (2020). *Design Science Research Process: A Model for Producing and Presenting Information Systems Research*. ArXiv.org. https://arxiv.org/abs/2006.02763

Platform CB'23 (2019). *Kernmethode voor het meten van circulariteit in de bouw.*

Platform CB'23 (2020). *Paspoorten voor de bouw.*

Play, G., Store, A., Appstore, A., & Store, W. P. (2016). *Mobile Applications for the*. (2011), 545–550.

Pope, K. S., Butcher, J. N., & Seelen, J. (1995). Everything You Wanted to Know About the MMPI. *Journal of Personality Assessment*, *65*(1), 187–189. https://doi.org/10.1207/s15327752jpa6501_15

Rangan, B. V. (2014). Fly Ash-Based Geopolymer Concrete Fly Ash-Based Geopolymer Concrete. *Geopolymer Cement and Concrete*, *7982*(May), 68–106. https://doi.org/10.1080/13287982.2005.11464946

Ritzén, S., & Sandström, G. Ö. (2017). Barriers to the Circular Economy - Integration of Perspectives and Domains. *Procedia CIRP*, *64*, 7–12. https://doi.org/10.1016/j.procir.2017.03.005

Rostami, A., Sommerville, J., Wong, L. I., & Lee, C. (2015). Engineering , Construction and Architectural Management Article information : *Engineering, Construction and Architectural Management*, *22*(1), 91–107. https://doi.org/http://dx.doi.org/10.1108/09699981111098711 Downloaded

Rudolphi, J. (2018). Blockchain for a circular economy: explorative research towards the possibilities for blockchain technology to enhance the implementation of material passports. https://pure.tue.nl/ws/portalfiles/portal/97558362/Rudolphi_0913284.pdf

Scheres, B., & Schüttrumpf, H. (2019). Enhancing the ecological value of sea dikes. *Water (Switzerland)*, *11*(8). https://doi.org/10.3390/w11081617

Schoenmaker, R., Verlaan, J., & van den Boomen, M. (2018). *Collaborative Design and Engineering: Study guide 2018*. (April).

Shen, W., Hao, Q., Mak, H., Neelamkavil, J., Xie, H., Dickinson, J., … Xue, H. (2010). Systems integration and collaboration in architecture, engineering, construction, and facilities management: A review. *Advanced Engineering Informatics*, *24*(2), 196–207. https://doi.org/10.1016/j.aei.2009.09.001

Solar Impulse. (2018). *Madaster - Solar Impulse Efficient Solution*. @Solarimpulse. https://solarimpulse.com/efficient-solutions/madaster

Stefanakis, P. (n.d.). *Digitalizing the construction site management UNIVERSITY OF TWENTE*.

Tasca, P., & Tessone, C. J. (2019). A Taxonomy of Blockchain Technologies: Principles of Identification and Classification. *Ledger*, *4*. https://doi.org/10.5195/ledger.2019.140

Torstensson, L. A. (2016). *Internal barriers for moving towards circularity - An industrial perspective*. 94. Retrieved from http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A968870&dswid=9804

Versteeg Conlledo, A. (2019). Managing circular construction projects. 1. Tudelft.nl. https://repository.tudelft.nl/islandora/object/uuid:23c11cff-1b6f-4a73-869a-9e29d1542ed1?collection=education

Wang, Q., Mitsumura, N., Chen, Q., Sarkar, A., Kurokawa, H., Sekiguchi, K., & Sugiyama, K. (2014). Investigation of condensation reaction during phenol liquefaction of waste woody materials. In *International Journal of Sustainable Development and Planning* (Vol. 9). https://doi.org/10.2495/SDP-V9-N5-658-668

Wolfs, R. J. M. (2015). 3D PRINTING OF CONCRETE STRUCTURES GRADUATION THESIS R.J.M. Wolfs. *Thesis of Eindhoven Univaersity of Technology*, 110. Retrieved from https://pure.tue.nl/ws/files/47026521/795000-1.pdf

Xinyi, Y., Yi, Z., & He, Y. (2018). Technical Characteristics and Model of Blockchain. *2018 10th International Conference on Communication Software and Networks, ICCSN 2018*, 562–566. https://doi.org/10.1109/ICCSN.2018.8488289

Yao, Z. T., Ji, X. S., Sarker, P. K., Tang, J. H., Ge, L. Q., Xia, M. S., & Xi, Y. Q. (2015). A comprehensive review on the applications of coal fly ash. *Earth-Science Reviews*, *141*, 105–121. https://doi.org/10.1016/j.earscirev.2014.11.016

Zanten, E. Van, & Adriaanse, L. A. (2008). *Reduced tide*. (May).

Zheng, Z., Xie, S., Dai, H., Chen, X., & Wang, H. (2017). An Overview of Blockchain Technology: Architecture, Consensus, and Future Trends. *Proceedings - 2017 IEEE 6th International Congress on Big Data, BigData Congress 2017*, (July), 557–564. https://doi.org/10.1109/BigDataCongress.2017.85

ZHOU, H., WANG, H., & ZENG, W. (2018). Smart construction site in mega construction projects: A case study on island tunneling project of Hong Kong-Zhuhai-Macao Bridge. *Frontiers of Engineering Management*, (March). https://doi.org/10.15302/j-fem-2018075

Government of the Netherlands (2016) A Circular Economy in the Netherlands by 2050 *p. 59* .Government.nl. https://www.government.nl/documents/policy-notes/2016/09/14/a-circular-economy-in-the-netherlands-by-2050

Zhang, R., Xue, R., & Liu, L. (2019). Security and Privacy on Blockchain. ACM Computing Surveys, 52(3), 1–34. https://doi.org/10.1145/3316481

Glossary –HLF(2021) Hyperledger-fabricdocs master documentation. Readthedocs.io. https://Hyperledger-fabric.readthedocs.io/en/release-2.2/glossary.html

Appendix

Interview-1

Name: [redacted]
Role in the company: **Innovation Manager**
Name of the Company: **Province of Noord-Holland**

Note: The data provided by the interviewee will be used for the research purpose only.

By 2050, the government wants to create a circular economy that only employs reusable raw materials. By 2030, one intermediate target is to minimise the consumption of virgin materials by 50%. Material reuse is one strategy to achieve circularity in the built environment. However, the exchange of materials between diverse stakeholders is hampered by a lack of information and a material exchange mechanism. As a result, material passports were created. The information regarding all the materials used in the building will be made available through these material passports. A blockchain-based framework is developed in this research to overcome the challenges of implementing material passports.

This is a two-fold interview. Through this interview, we will be able to find and validate the barriers and opportunities of a material passport through the experience of the stakeholders and validate the new blockchain-based material passport framework.

1. Why is using material passports important to you?

   The idea was producing resources cost a lot of time and labour. So definitely, you need to create them so that you can reuse them, or at least close this cycle. Due to the Industrial Revolution, things change in a paradigm shift. Let's say and start producing, producing and producing, not thinking about reusing as much as possible because materials are abundant. To facilitate the reuse of materials, the supply chain requires coordination and to organise for this involves information. I think the information technologies, the solutions information technology is provided to us, are why we can start thinking about the circular economy because we solve a lot of the technological problems that we encounter. We try to solve that coordination problem of how materials flow through supply chains and how they should be allocated back to the different parties in that supply chain or value chain. So that's why I think a materials passport is so valuable, is it is that part is that footprint digital footprint of a product or composite product that can give that information to parties to reuse and to think about a more circular solution

2. Do you agree with the data parameter given below, or are there any other parameters to be considered?

   In the use phase, it is essential to have Performance data of the building because if you have performance data, you know what is going on throughout the building/material lifecycle.

3. What are the barriers that can hinder the application of material passports in your process? Are there any other barriers that the ones shown here?

Provision of Information	• No incentive for providing the data • Non availability of the data *I think the non-availability of the data's also a big problem; we do not know what we have, at least not sufficient, and in the quality that we would like to have it. And it's also not often we can either generate the data to go to an object and analyse it and decompose it into its is different components and then generate the data by looking and analysing. But if you look at the drawings, there is like the logistics data, for instance, a building, that those don't exist. So that's a barrier* • Some actors do not want to be transparent (Confidentiality issue) *There is always tension between organizations. There is no clear there is no cooperation is still a thing in the construction industry. So I would do would also think that's a barrier, especially when it comes to data.*
Storage of Information	• Ownership rights on the data *Ownership here is, is a particular issue that is that has no clear solution. When I look at the digital digitization projects that I'm involved in, what do we do with our generated data? Who's the owner? Who gets the rights for what kind of functions of data manipulation. But I would also say that is not only the ownership of the data but also the amount of barrier; we need to aggregate information in meaningful ways to save space and save energy because we keep those that data in place as it is over 100 years.*
Access to Information	• Every actor cannot have complete access to all the data present on the material passport. It is important to have different access levels to see different data.
Quality of Information	• Managing the quality assurance of the data in the material passports. This raises the question when data is inaacurate, who is liable for the aftermath. *The fragmented nature of the construction industry. If you look at homeowners, and well, there's plentiful of those. And especially, and just regional governments, local governments owning their share of infrastructure, you also have a coordination issue. And accessibility is critical here because I*

	think you would also like to be able to cross-reference. Yeah, I agree with that one quality of information • No standard for a material passport
Presentation of Information	• Lack of uniformity/standard in the data within built environment.

Other Barriers:

***The usability of the information**. For the material passports to be present in the industry, it needs to add value. And for something to add value, it needs to be usable. Until now, the usability of the material's passport has not been proven.*

***The integration of the materials passport in our business** as usual is another barrier. From the asset management perspective, how material passports will integrate with digital twins and become dynamic.*

4. What are the opportunities that can simulate the use of material passports?

*Making the **data in the material passport more dynamic** by linking it with other systems. If this can be achieved, then material passports will have an added value. **Data Continuity** also implies that it is relevant, and it can say something it's actual, and you can draw conclusions throughout the lifecycle. Instead of just knowing where it came from and when you want to decompose the structure, knowing how it's built up. I think there's a lot in between those two points that we need to address by then. Continuity is part of that solution*

Blockchain technology:

5. Do you know about the concepts of blockchain technology?
   Yes, I do.

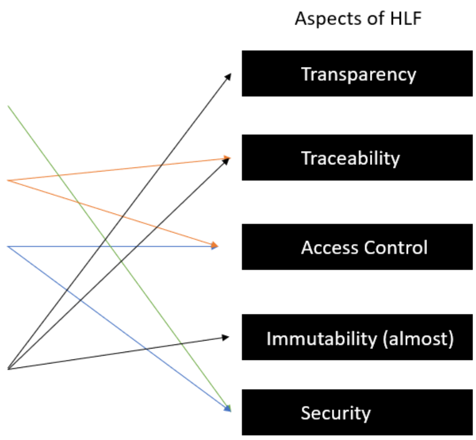
6. What do you think blockchain as an improvement for your process?

   - *I think blockchain is a solution for this problem because they can be an owner of their data.*
   - *Create these different layers of accessibility throughout the blockchain by using your unique identification codes*
   - *It is unique and traceable; you can also display transparency. Even though you do not see all of the information, you see the path and journey.*
   - *I think blockchain is a concept of validation and distributed in nature.*

7. Do you see private permissioned blockchain (Hyperledger fabric) as a good fit for the material passport?

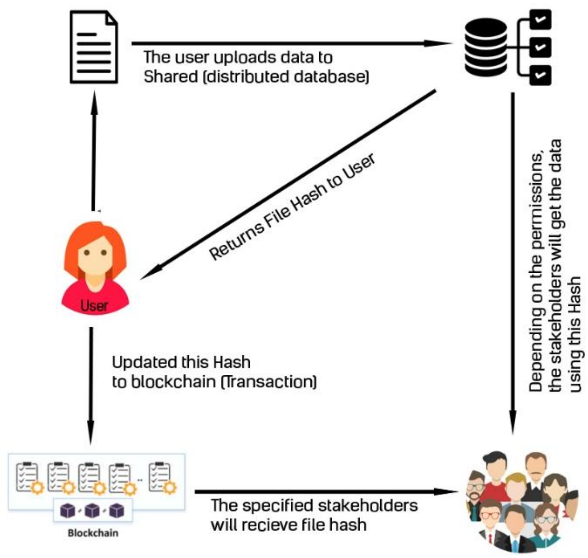
Barriers of Material Passports

Provision of Information	• Some actors do not want to be transparent (Confidentiality issue)
Storage of Information	• Ownership rights on the data
Access to Information	• Every actor cannot have complete access to all the data present on the material passport. It is important to have different access levels to see different data.
Quality of Information	• Managing the quality assurance of the data in the material passports. This raises the question who is responsible for the consequences when the data is not correct.



The blockchain's scalability issue needs to be solved for which a private-permissioned blockchain (HLF) can be used. However, this technical solution also creates a social problem: the coordination and the organization required. So, the governance and organization required on a social level institutional level to facilitate the notion of creating blockchains, in which materials passports are constructed

8. What are your thoughts about the suggested framework?



9. From your perspective, what are the biggest hurdles to overcome?
    - *Standardizing the material passport for projects.*
    - *Using a same platform for multiple projects.*

Interview -2

Name: [redacted]
Role in the company: **Architect (Consultant)**
Name of the Company: **Copper8**
Years of experience: **3.5 years**

Note: The data provided by the interviewee will be used for the research purpose only.

By 2050, the government wants to create a circular economy that only employs reusable raw materials. By 2030, one intermediate target is to reduce the consumption of primary raw materials by 50%. Material reuse is one strategy to achieve a circular economy in the built environment. However, the exchange of materials between diverse stakeholders is hampered by a lack of information and a material exchange mechanism. As a result, material passports were created. The information regarding all the materials used in the building will be made available through these material passport. A blockchain-based framework is developed in this research, to overcome the challenges of implementing material passports.

This is a two-fold interview. Through this interview, we will be able to find and validate the barriers and opportunities of a material passport through the experience of the stakeholders and validate the new blockchain-based material passport framework.

Do you use material passports in your current process? If not, how can you include them?

Since I am a consultant, as a company ourselves, we do not use material passports, as we do not develop/construct anything. However, we do have clients for whom material passports are an opportunity. Therefore in my response to the questions, I have answered them as a consultant for clients (public governments) who do/could use material passports.

Our clients, mainly public governments such as Provincie Noord-Holland and housing associations, do use material passports. However, it is not something that is embedded into their primary processes. Mostly a material passport is made for a pilot project, where the organization is not sure of the use of the passport yet. The next step for these organizations is to find out in what way the passport can be used in their regular processes

1. Why is using material passports important to you?

   The use of the material passports isn't important yet. Mostly the organizations believe in the future use of passports. Particularly the fact that it helps them get insight in the materials that are in objects/buildings for future re-use. They believe that it is crucial to have passports to be able to reuse materials in the future.

2. What are the barriers that can prevent the use of material passports in your process? Are there any other barriers than the ones shown here?

Provision of Information	• No incentive for providing the data • Non availability of the data • Some actors do not want to be transparent (Confidentiality issue)
Storage of Information	• Ownership rights on the data .
Access to Information	• Every actor cannot have complete access to all the data present on the material passport. It is important to have different access levels to see different data.
Quality of Information	• Managing the quality assurance of the data in the material passports. This raises the question who is responsible for the consequences when the data is not correct. • No standard for a material passport
Presentation of Information	• Lack of uniformity/standard in the data within built environment.

As of this moment, there are no standard material passports. Many organizations are experimenting with the phenomenon 'material passports', meaning everybody interprets and uses it. Because there is so much unclarity about the technical outline of a material passport, at this moment, it costs a lot of time and money to make a passport. At the same time, the use of the material passport is still unclear. This makes it hard for organizations to invest much money.

3. What are the opportunities that can simulate the use of material passports?

   One of the biggest steps into stimulating the use of material passports is to standardize the material passport for a sector. As Copper8 we did a research to material passports in the road construction sector (GWW-sector in Dutch). One of the main outcomes of this research is to start an initiative as the government of the Netherlands to standardize material passports. Meaning the way data is saved, which data is saved, where it's saved, et cetera. When this is standardized, organizations themselves don't have to make this step themselves, making it easier to use passports.

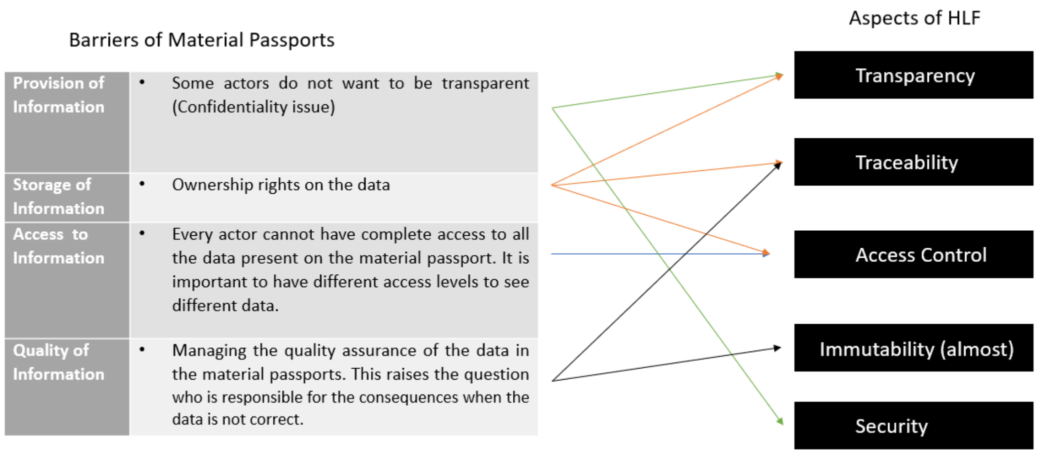
Blockchain technology:

4. Do you know about the concepts of blockchain technology?

   I know about the concept of Blockchain in a general way.

5. What do you think blockchain as an improvement for your process?

   I think Blockchain could be one of the technical solutions to help stimulate material passports. However, it is merely that, a technical solutions. Material passports however are not a technical goal on itself, it is a mean tot he goal of circularity. Meaning that besides possibly using blockchain technology for passports, organisations still have to organize processes around the material passports as well. If they don't see a use for material passports, it won't be implemented anyway, even when there is blockchain. So yes it could be an improvement, but not when you solely focus on it.

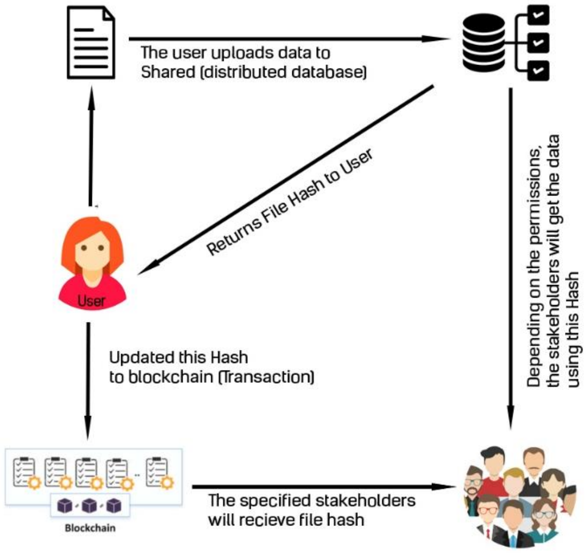


6. Do you see private permissioned blockchain (Hyperledger fabric) as a good fit for the material passport?

   Yes, because a shared database with multiple stakeholder providing data is requires. In addition to this a tamperproof log of data is needed that doesn't allow data deletion or change in the data. Since, the intellectual property will be shared on blockchain, it is necessary to predefine the access rights of users.

7. What are your thoughts about the suggested framework?

   I think as a framework it is a good way of approaching the material passport. But as mentioned in question 7, the framework is just a technical solution for the passport. I believe that we are able to make passports work technically, but this is not the only challenge we face. We have to combine an approach of technical, process and financial



8. From your perspective, what are the biggest hurdles to overcome?

   As of this moment there often is a split incentive for the material passports. The makers of the passport have to invest time and money in the passport, while the benefits of the passport are more on the long-term. Often that party isn't in the picture anymore, meaning that one has to invest in something while someone else gets the benefits of it.

9. Do you see other opportunities that might benefit from blockchain technology?

   Right now I do not.

Interview-3

Name: [redacted]
Role in the company: **Consultant**
Name of the Company: **Alba Concepts**

Note: The data provided by the interviewee will be used for the research purpose only.

By 2050, the government wants to create a circular economy that only employs reusable raw materials. By 2030, one intermediate target is to reduce the consumption of primary raw materials by 50%. Material reuse is one strategy to achieve a circular economy in the built environment. However, the exchange of materials between diverse stakeholders is hampered by a lack of information and a material exchange mechanism. As a result, material passports were created. The information regarding all the materials used in the building will be made available through these material passport. A blockchain-based framework is developed in this research, to overcome the challenges of implementing material passports.

This is a two-fold interview. Through this interview, we will be able to find and validate the barriers and opportunities of a material passport through the experience of the stakeholders and validate the new blockchain-based material passport framework.

Do you use material passports in your current process?

> *We use material passports for calculating BCI and also advice our client to use material passports. This is because it gives clarity on the material data especially in the use phase and facilitated efficient maintenance process, of course embedding circularity principles. I think it's, it's really nice to have a few of how it works, and especially which data you need, because now we see in the market that is, the level of detail is kind of confusing. So how far you need to actually go with level of detail of the materials*

1. What are the barriers that can prevent the use of material passports in your process? Are there any other barriers than the ones shown here?

   The building sector is not at modern as IT sector. There needs to be an attitudinal change amongst the people working in the construction industry and I think it is one of the hardest thing to do. There is no incentive for people who are involved in the project for a short duration. The other major barrier is the usability of material passport, like who uses it and why is it being used is still kind of unclear.

2. What are the opportunities that can simulate the use of material passports?

   One of the biggest steps into stimulating the use of material passports is to standardize the material passport for a sector.

Blockchain technology:

3. Do you know about the concepts of blockchain technology?

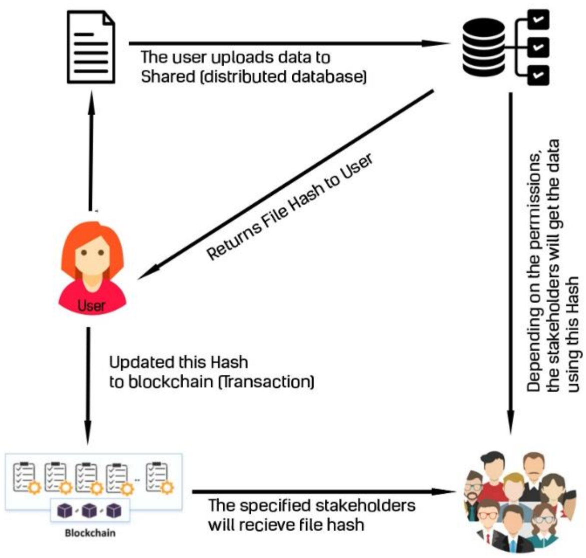
   I know about the concept of Blockchain in a general way.

4. What do you think blockchain as an improvement for your process?

   Yeah, I think in theory, it should work.

5. What are your thoughts about the suggested framework?

I think as a framework it is a good way of approaching the material passport. This is this is actually a smart solution and the framework as well, I think blockchain could really help the industry by generating more through passports and make sure to save the data in the right way.



6. From your perspective, what are the biggest hurdles to overcome?

As mentioned earlier, the change in attitude must take place to try novel technologies and use cross-sectoral solutions.

Interview-4

Name: [redacted]

Role in the company: **Project Coordinator, Data and Circular Business Innovation**

Name of the Company: **New horizon Urban Miming BV**

Note: The data provided by the interviewee will be used for the research purpose only.

By 2050, the government wants to create a circular economy that only employs reusable raw materials. By 2030, one intermediate target is to reduce the consumption of primary raw materials by 50%. Material reuse is one strategy to achieve a circular economy in the built environment. However, the exchange of materials between diverse stakeholders is hampered by a lack of information and a material exchange mechanism. As a result, material passports were created. The information regarding all the materials used in the building will be made available through these material passport. A blockchain-based framework is developed in this research, to overcome the challenges of implementing material passports.

This is a two-fold interview. Through this interview, we will be able to find and validate the barriers and opportunities of a material passport through the experience of the stakeholders and validate the new blockchain-based material passport framework.

1. Do you use material passports in your current process? If not, how can you include them?
   Within New Horizon, we use a stripped-down version of a materials passport. At the start of a project we make a so-called harvest survey of the building. Here we make an inventory of the elements, building products and materials present, including their properties such as quality, quantity, etc

2. If you use them (see question 1), why is using material passports important to you?

   To inventory what usable elements, building products and materials are in the building.

3. Do you agree with the data parameter given below or are there any other parameters to be considered?
   Yes

	Data Input by stakeholder	Data requirement from passport
Urban Miner	Financial Value Log Disassembly Supplier (as Urban Mine) Owner (as Urban Mine)	Circular Performance Disassembly possibilities Date Release Manual Disassembly Log Maintenance Log Management Log Assembly Supplier Location Completion Owner Technical Lifespan Build-up Material Re-use Material Loop Toxic Level Material

4. What are the barriers that can prevent the use of material passports in your process? Are there any other barriers than the ones shown here?

The biggest barrier is the reliability of the data: how can we as Urban Miner be sure that the data in a passport has been maintained and is therefore correct?

Provision of Information	• No incentive for providing the data • Non availability of the data • Some actors do not want to be transparent (Confidentiality issue)
Storage of Information	• Ownership rights on the data
Access to Information	• Every actor cannot have complete access to all the data present on the material passport. It is important to have different access levels to see different data.
Quality of Information	• Managing the quality assurance of the data in the material passports. This raises the question who is responsible for the consequences when the data is not correct. • No standard for a material passport
Presentation of Information	• Lack of uniformity/standard in the data within built environment.

5. What are the opportunities that can simulate the use of material passports?

A Government Policy on Material passport and Global open standard or norm.

Interview-5

Name[redacted]
Role in the company: **Design Leader**
Name of the Company: **Strukton Worksphere**
Years of Experience: **4**

Note: The data provided by the interviewee will be used for the research purpose only.

By 2050, the government wants to create a circular economy that only employs reusable raw materials. By 2030, one intermediate target is to minimise the consumption of virgin materials by 50%. Material reuse is one strategy to achieve a circularity in the built environment. However, the exchange of materials between diverse stakeholders is hampered by a lack of information and a material exchange mechanism. As a result, material passports were created. The information regarding all the materials used in the building will be made available through these material passport. A blockchain-based framework is developed in this research, to overcome the challenges of implementing material passports.

This is a two-fold interview. Through this interview, we will be able to find and validate the barriers and opportunities of a material passport through the experience of the stakeholders and validate the new blockchain-based material passport framework.

1 Do you use material passports in your current process? If not, how can you include them?

No, in my current role I'm not using material passports. At Strukton we do see clients ask in tenders for a material passport. Often we suggest Madaster or a BIM-model as a solution. So, for 1 Client I know my colleagues are working on a BIM-model which will be used as a material passport.

2. Why using material passports is Important to you?

It is import to know the decomposition (raw materials; components; systems; ..) of your building. In my current role as Design Leader I need to know what I'm design-ing; in what context. Therefore a good understanding of the building as a whole ánd it's parts is key. If this decomposition is secured in a material passport, then this could be valuable.

3. What are the barriers that can hinder the application of material passports in your process?

The biggest barrier I see, and have seen in my time at de Architekten Cie., is that we forget the first step: In your examples shown, you speak of barriers related to 'information'. But in my opinion the first major step is to decompose a building in it's parts (doors; floors; windows; ..). If this is done correctly, only then we can start linking 'information' to this parts. In this first step is a lot to win. Because a building is a complex layered system, it's difficult to pull apart the building in it's parts in their correct level.

4 What are the opportunities that can simulate the use of material passports?

I think they are enormous. If you truly understand a building as a complex layered system, and you can catch / translate that into a material passport the opportunities are endless. For example: Spotify truly knows the system of music (artists; labels; numbers; genres; ..). And because of this, they can serve their clients as never before. LinkedIn and Facebook truly knows the system of communities (friends; acquaintances; colleagues; ..). In my opinion this kind of innovation is also possible for the built environment.

Blockchain technology:

4. Do you know about the concepts of blockchain technology?
Yes, I have heard about it, but don't understand it from technical point of view.

5. What do you think blockchain as an improvement for your process?

I'm sure linked data is a must, for linking different data streams. The question 'Do you want a tamperproof log of al writers ..' I would like to answer 'yes'. But I've learned that a building process is built on trust. That's why building contractors like to work with known suppliers etc. So maybe Blockchain is overkill for now. But yes I think eventually this will be necessary. Every improvement to storage and simple access to correct information is welcome. In my current role the most of the time I'm busy with finding the correct information.

6. Do you see private permissioned blockchain (Hyperledger fabric) as a good fit for the material passport?

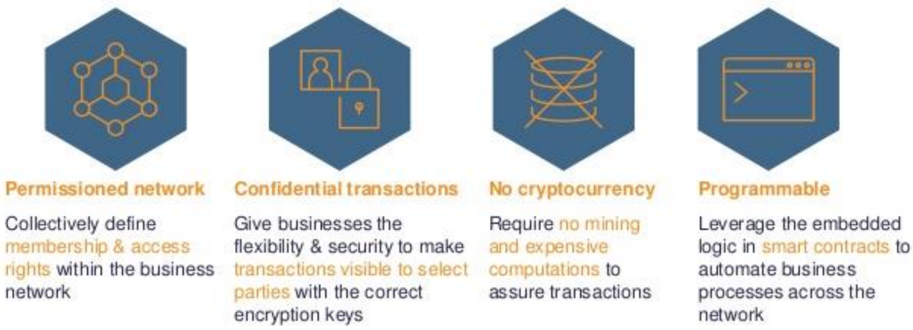


Figure 45: Features of Hyperledger Fabric

I am not technically sound to answer the question

Interview-6

Name: [redacted]
Role in the company: **Chief Technical Officer**
Name of the Company: **Excess Materials Exchange**
Years of Experience: **20 years**

Note: The data provided by the interviewee will be used for the research purpose only.

By 2050, the government wants to create a circular economy that only employs reusable raw materials. By 2030, one intermediate target is to minimise the consumption of virgin materials by 50%. Material reuse is one strategy to achieve a circularity in the built environment. However, the exchange of materials between diverse stakeholders is hampered by a lack of information and a material exchange mechanism. As a result, material passports were created. The information regarding all the materials used in the building will be made available through these material passport. A blockchain-based framework is developed in this research, to overcome the challenges of implementing material passports.

This is a two-fold interview. Through this interview, we will be able to find and validate the barriers and opportunities of a material passport through the experience of the stakeholders and validate the new blockchain-based material passport framework.

My name is [redacted] *and I've been working in the tech industry for the last 20 years, I have my own technology consulting company into blockchain and machine learning. Last two to three years, I've been writing a lot of solutions regarding digital twins and material passports or electronic product passport for European Union. But also for private companies like Excess Materials Exchange and for World Economic Forum for global battery passport for electrical car batteries. With Excess Material Exchange, we build digital platform, both public and private, or based on Hyperledger fabric blockchain. And last month, I also started working on a new platform idea for International Trade Finance, which also includes digitizing products and creating a digital twin with not only with product passport, but also with IoT solutions.*

1 Why is using material passports important to you?

A lot of materials are not registered in a digital way. These products are lying across warehouses and production units and they are not registered, which means the information cannot be shared properly. So you do not have enough information or data points of the condition, the quality, the location, and the volume. So with the material passport, you can capture those information. The first challenge is digitizing these physical products.
if you can digitize it, you get information and you can create a knowledge and wisdom out of it. That's where you can do a lot of analytics, predictive analytics to not only share or increase the circular use of these products, but also find ways to create or reduce waste.

2 What are the barriers that can hinder the application of material passports in your process? Are there any other barriers that the ones shown here?

Provision of Information	• No incentive for providing the data • Non availability of the data • Some actors do not want to be transparent (Confidentiality issue)
Storage of Information	• Ownership rights on the data
Access to Information	• Every actor cannot have complete access to all the data present on the material passport. It is important to have different access levels to see different data.
Quality of Information	• Managing the quality assurance of the data in the material passports. This raises the question when data is inaacurate, who is liable for the aftermath. • No standard for a material passport
Presentation of Information	• Lack of uniformity/standard in the data within built environment. *If you do not have the right standards, and people are not adhering to a certain standard or uniform data structure to a data model, then your interoperability becomes a big issue.*

The other challenge is once you digitize this information, how do you share this information with your trade partners and other stakeholders as they contain confidential information related to materials and products such as Intellectual property. So it's also very important to exchange these information in a secure and private way. Apart from that I see that you have covered the major barriers.

3 What are the opportunities that can simulate the use of material passports?

As mentioned earlier, to exchange the information is a secure and private way. Have a uniform data structure to overcome interoperability issues.

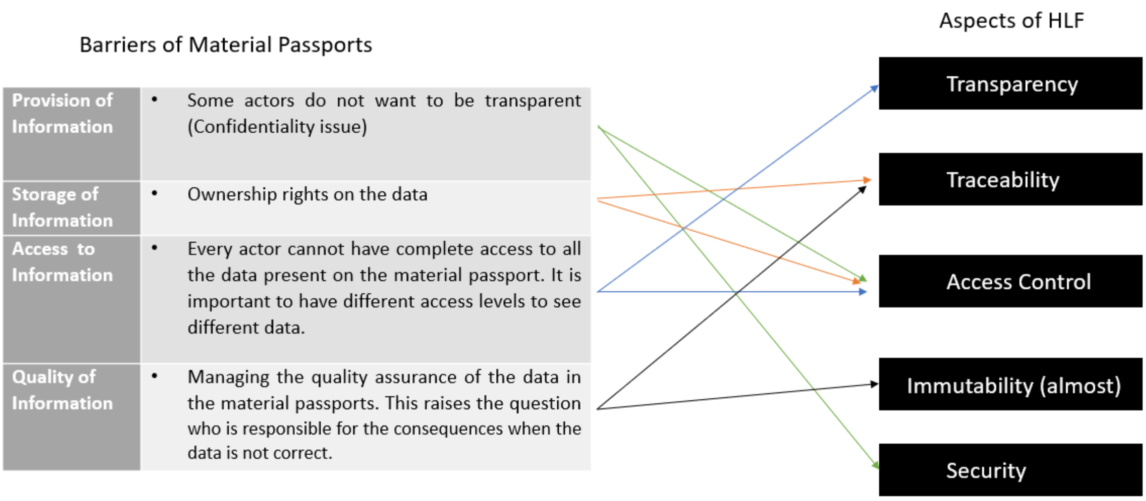
Blockchain technology:

4 What do you think blockchain as an improvement for your process?

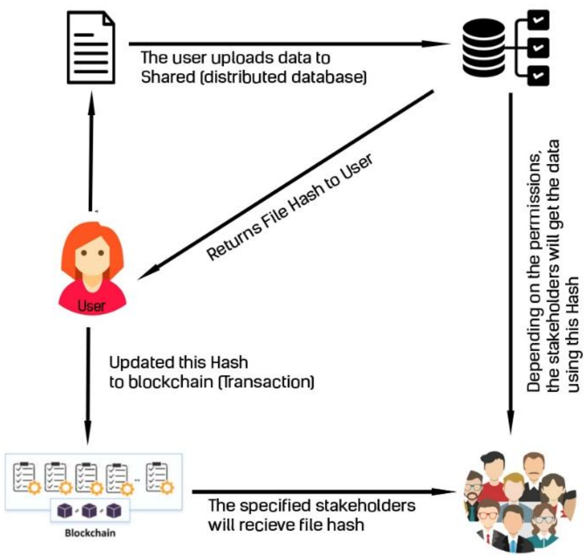
The decentralized or a distributed system like blockchain is definitely a big plus today. If you can explore something which is already built like ethereum or Hyperledger, to name a few, especially around privacy, secure data sharing. So indeed, I think there's a nice use case about using blockchain in this kind of setup, especially when there are multiple parties and you need consensus. Automated contracts, right, like smart contracts to make things more efficient. So there is a nice use case.

5 Do you see private permissioned blockchain (Hyperledger fabric) as a good fit for the material passport?

Yes, I think HLF is a great fit and would be a promising use case in this setup.



6 What are your thoughts about the suggested framework?



I think this is this nicely explained. Also very simplistic version. So it's very nice. The use of shared database can be considered as a spear fishing approach. Storing all your raw data in MangoDB or any other database and the hash flows from database to blockchain network. You send something to get the information out of it. It's so true. So it is the spear fishing polyglot approach, indeed. So you do on chain and off chain, depending on the size and the payload. Because if you should store everything in a blockchain, how would you do *a machine learning out of it on a hash information, right. So this is your on chain and off chain. Also, what we wrote in our architecture is we want to store raw data on off chain. That's where you want to do more analytics learnings and everything, but you only want to create, or we only want to store the confidential information, the things that you want on blockchain in a hash format, which will have a pointer to your database. Again, spearfishing back, if you want to validate something, which will actually reward right*

7 From your perspective, what are the biggest hurdles to overcome?

*I think education***,** *because when you take a blockchain use case to any industry, especially the construction industry, which is more follower than a leader right as compared to finance and e-commerce, you have to educate them the benefits of blockchain and why you want to use.*
Second is making sure that you bring all the part interested parties into equation, because you're talking about the decentralized setup, you should have centralized setup. So you really have to bring more than two consortium members, before we can set up a nice network.
The third part, which is also important is the whole administration around setting up the consents, setting up different nodes who manages the GDPR around it, the processor, the controller and the owner of the data and the infrastructure.