MASTER

Blockchain for a circular economy

explorative research towards the possibilities for blockchain technology to enhance the implementation of material passports

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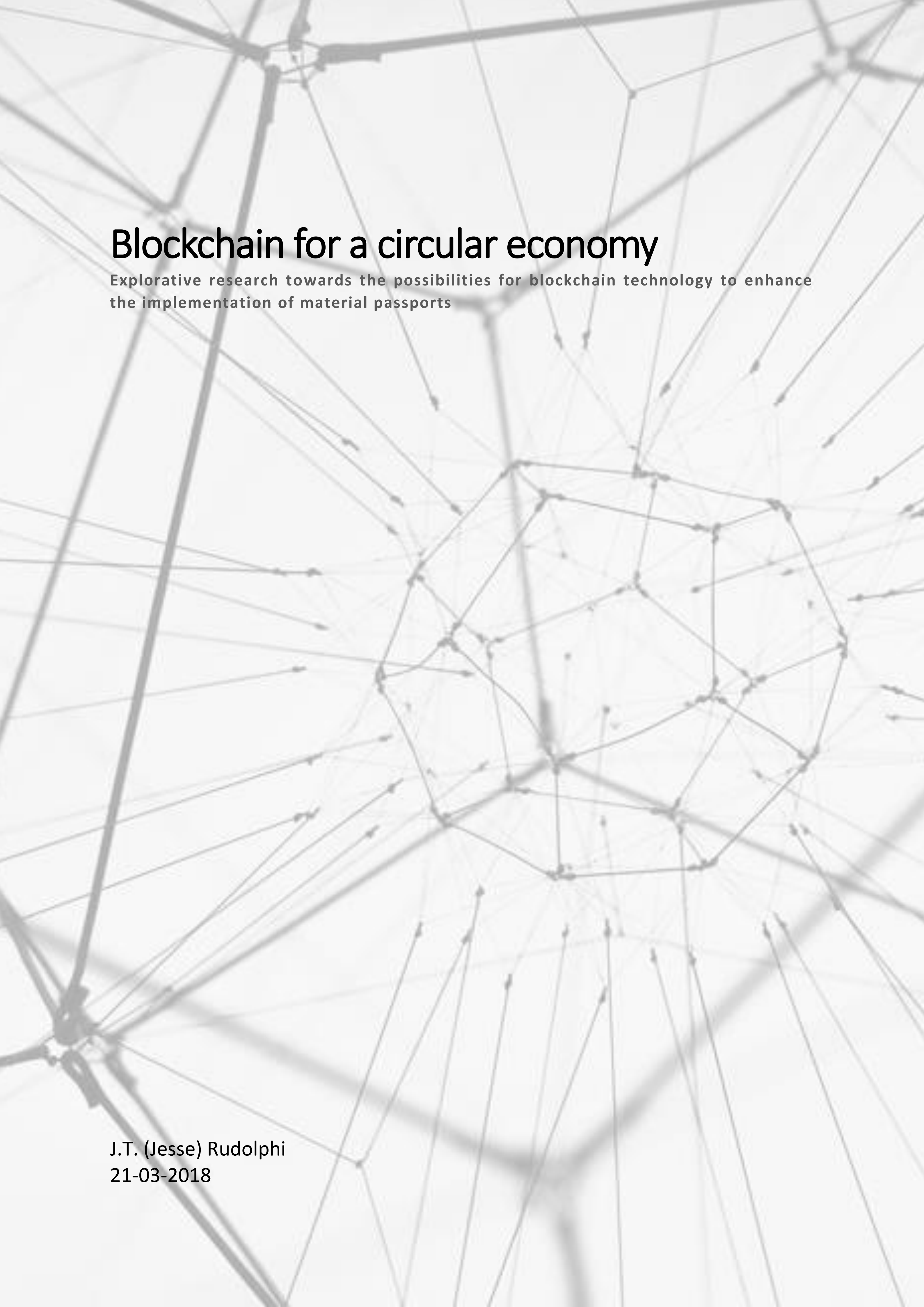

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Title
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Explorative research towards the possibilities for blockchain technology to enhance the implementation of material passports

Master thesis

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“ANYONE WHO BELIEVES IN INDEFINITE GROWTH IN ANYTHING PHYSICAL, ON A PHYSICALLY INFINITE PLANET, IS EITHER MAD OR AN ECONOMIST”

Kenneth E. Boulding

Preface

The commitment on conducting the research for this thesis spans over the course of sixth months. During this timeframe much was learnt. It was a meaningful journey, both in terms of conducting academic research and also gaining personal and practical experience on both topics. This research could not have been executed without the contribution of many professional people, who did not hesitate to share their knowledge about the topics with me.

First and foremost, I would like to offer my gratitude towards the whole team of Group Innovation at ABN AMRO and specially to Alexa Krayenhoff for her guidance, patience, and encouragement through the whole journey. I have been given a lot of freedom in pursuing my ideas and follow my own path. This was also combined with regular and constructive feedback that helped me keep on track along this journey. Also I want to thank Tristan Kunen from Brink Management / Advies for his contribution from the real estate perspective. Moreover, their contribution was essential to ensure the practical relevance of this research.

Second, I would like to offer my gratitude to my university supervisors Qi Han and Marleen Hermans for their guidance throughout the project. Also from the university I have been given a lot of freedom in pursuing my ideas on this new area. Their contribution was essential to ensure academic rigor and scientific validity in this research.

Traveling the path of this research was sometimes a long and difficult process. Understanding the real value of what the interaction is between those innovative and disruptive technologies is a process that not only requires commitment but also persistence. I sincerely thank all the respondents from the business that wanted to make time free to give me an insight in their view on both material passports and blockchain technology. Their experience and expertise were essential for analysing this new area within the real estate sector.

At a personal level, I am very thankful for the different discussions that I conducted with Jochem de Vos. In the parts of this journey where I did not immediately see how I should approach the research path, the conversations with Jochem helped me in going back to the essence of the problem. Last, but not least, I want to thank my parents and sister, Meindert, Elsbeth, and Crissy Rudolphi for their support and motivation during this project. The support from each of them was important throughout my time as a student as well as in accomplishing this research. Looking back, this journey was a beautiful conclusion for my time as a student.

I wish you to enjoy reading this report as much as I enjoyed writing it.

Jesse Rudolphi
Utrecht, 2018

Management summary (English)

Abstract

The current linear economy is based on the take-make-dispose model. This model is structured around the consumption of goods instead of keeping them at their highest value. If this model continues to be the most dominant approach the scarcity of raw materials will increase, which will drive up costs and price volatility. The linear economy not only creates problems regarding raw materials but also has a large impact on the environment. The use of products within the take-make-dispose model creates tremendous amounts of waste. The concept of a circular economy minimizes these streams of waste. A lack of information is often cited as a main problem that lead to waste. Therefore, material passports are created to fill this information gap; however, material passports face barriers that could prevent their use. Using semi-structured interviews, there is analysed which opportunities, barriers, and requirements are viewed as key within the market when people use material passports. These opportunities, barriers, and requirements will make a comprehensive list of aspects that are important for material passports. This study analysed which aspects can be addressed through blockchain technology. Concluded from the outcomes can be stated that blockchain technology can be used as a validation for material passports. The public permissionless blockchain can be used to validate all the data entries and adjustments within the material passport. This creates one truth within the network that is accessible by all participants. Within the blockchain it is always visible who the owner is and who has made what adjustments to the data. This enhanced scenario is discussed regarding the aspects of provision, storage, access, quality, presentation, and the process of giving information. The research contributes to the field by outlining important aspects of a material passport, identifying how these aspects could be addressed with blockchain technology, and conceptualising an enhanced material passport with blockchain technology. Possibilities for further research are discussed.

Time for a new model

The origins of the current linear economy, the take-make-dispose model, date back to the industrial revolution. The last 150 years of industrial evolution have been dominated by this linear model, in which goods are manufactured from raw materials, sold, used, and finally thrown away as waste (Ellen MacArthur Foundation, 2013a). Continuing this pattern will increase the scarcity of raw materials which will drive up input costs and price volatility when access to new raw materials becomes more challenging and expensive (Ellen MacArthur Foundation, 2013a). This could threaten the supply in the future, because natural raw materials such as minerals are finite and many reserves are already very limited (Andrews, 2015; Ellen MacArthur Foundation, 2013). The Dutch built environment is 90% dependent on raw materials like iron, aluminium, copper, clay, limestone, and wood (Odijk & Bovene, 2014). The linear economy not only creates problems with regarding material scarcity but this model has also a great impact on the environment. The usage of products in the take-make-dispose model, results in large amounts of waste. Some of this waste is recycled but much is assigned as landfill. The current way of recycling is suboptimal and is also referred as downcycling. The recovered materials from recycling are of lower quality than the original materials (Odijk & Bovene, 2014).

A new way of thinking

In the last decade, the prices of natural resources increased and became more volatile. This change in the supply chain makes the change towards a new system necessary (Ellen MacArthur Foundation, 2013a). In a circular economy, the added value of products is maintained for as long as possible and waste is eliminated. To thoroughly integrate the concept of a circular economy, a new way of thinking is needed that will reshape the economy. The concept of a circular economy re-imagines how the material flows that move through the economy might be closed (Prendeville, Cherim, & Bocken, 2017). The Ellen MacArthur Foundation (2013a) describes the concept of a circular economy as follows:

"A 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. The concept distinguishes between technical and biological cycles."

A brighter future with material passports

The adoption of more circular business models promises a brighter future for the European economy. It would allow Europe to meet the current and future challenges of global pressure on resources and would reduce the rising insecurity of supply (European Commission, 2014a). The introduction of material passports is a concrete measure that can be of great help in stimulating reuse of materials by increasing transparency to develop a circular business case and enabling reallocation (Circle Economy, 2015). To understand the potential value of circular materials, products, and systems, a reliable set of information is necessary. Material passports are created with the aim of providing such information (Luscuere, 2017).

Opportunities with blockchain technology

Technology repeatedly emerges as a key aspect to enable circular loops, to connect demand and supply, and to handle, store, and manage the huge amount of data that a circular economy requires (Pomponi & Moncaster, 2017). Blockchain technology offers opportunities for new social processes. It has the potential to bring a circular economy closer, enables the sub-economy, increases transparency, and facilitates information about carbon footprints and the origin of materials (Dutch Blockchain Coalition, 2017). Blockchain is a game-changing innovation because for the first time in history, digital transactions can be made without having to rely on an intermediary (Ellen MacArthur Foundation, 2017b). It can also be used for immutable tracking of authenticity and provenance of both digital and physical products. This could revolutionize supply chain management, regulatory oversight, and intellectual property management (Bauman, Lindblom, & Olsson, 2016).

Barriers and requirements

The literature review and expert interviews showed that material passports still need to overcome certain barriers and requirements before they can be implemented widely. The expert interviews that were conducted were structured around the lifecycle of a building. Stakeholders from the initiative, construction, maintain, and reuse phase were interviewed. Based on their various answers, it can be stated that they recognized the material passport as an important tool to improve their own core process. The interviews showed that currently a data loss occurs between the different stages of the lifecycle of a building.

The interviewees recognised the material passport as a potential solution for this data loss. The interview data on different aspects related to opportunities, barriers, and requirements were analysed. Those aspects based on the opportunities, requirements, and barriers were combined to make a comprehensive list of aspects that are seen as important for material passports. The list can help to determine what aspects can be addressed with blockchain technology. An expert panel was consulted to determine which aspects can be addressed using the public permissionless blockchain. The public permissionless blockchain was used in this research as it illustrates the possibilities of the new technology. The full list appears in table 1, with aspects that are addressed by blockchain technology shown in black.

Table 1: Aspects of material passport related to blockchain

Aspects	# Covering code	Supplier	Architect I	Architect II	Advisor	Contractor	Maintainer	Facility manager	Owner	Urban Miner	Recycler	Municipality
Provision of the information	1 Reward system	x	x	x	x				x	x		x
	2 Only necessary information		x			x	x	x		x	x	
	3 Easy handling	x	x					x				
	4 Solving confidentiality	x	x				x					
	5 Cooperation supply chain				x		x					
	6 Data continuity					x			x			
	7 Standardisation of data		x			x						
	8 Predevined levels of detail	x										
Storage of the information	1 Clear ownership data	x	x	x			x		x			x
	2 One data source								x			
	3 Security	x										
Access of the information	1 Predefined who has access	x			x			x	x			
Quality of the information	1 Validation		x	x	x		x	x	x	x	x	
	2 Data management	x			x		x	x	x	x	x	x
	3 Determining real value					x		x	x	x	x	x
	4 Immutable		x	x	x	x	x					
	5 Traceability									x		
	6 Dynamic during the lifetime		x									
Presentation of the information	1 Uniformity	x		x	x	x	x	x	x		x	x
Process of giving information	1 Added value has to be clear	x			x							
	2 Information request at the beginning	x								x		
	3 Experiment								x			

Enhanced material passport with blockchain technology

In the enhanced situation, blockchain is added to the database in which the material passports are stored. The enhanced situation is shown in figure 1.

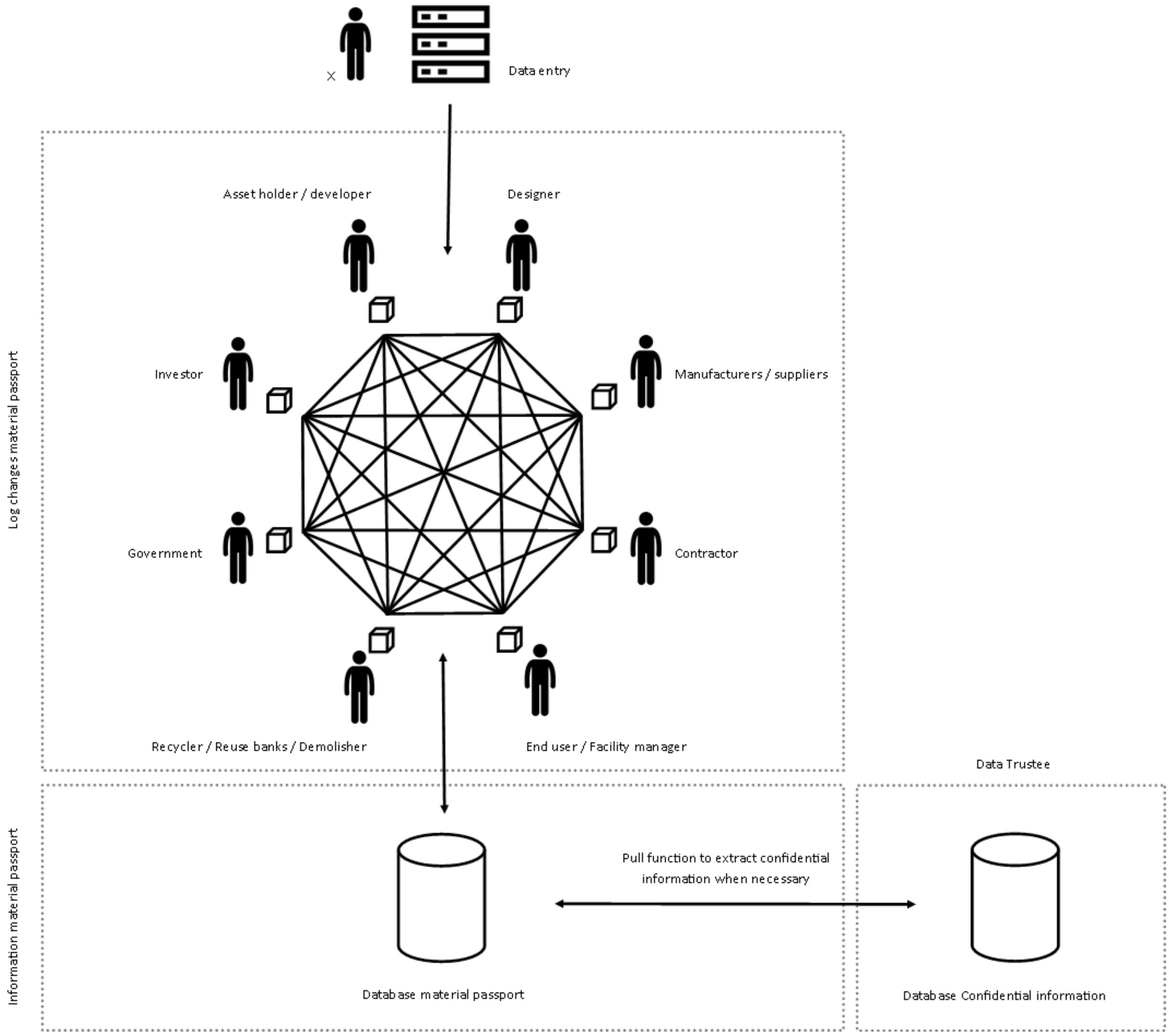

Figure 1: Enhanced situation material passport with blockchain technology (own illustration)

In the improved situation, information is still stored inside a database that is owned by the owner of the asset. The owner of the asset remains responsible for keeping the data up to date. Every company is responsible for providing its own information to the material passport, but the owner of the asset is the company that has the incentive to keep the material passport up-to-date. All new information that is provided for the material passport, and all adjustments, are logged inside the blockchain. Every participant can see who the owner is and who is responsible for specific data (Morabito, 2017). With the blockchain, it is possible to create one truth in the network such that all companies can verify whether they have the right information. When a mutation is verified and approved by the participating nodes, it is almost impossible to change or alter the mutation data. The process of a single rewrite on the blockchain is tedious and would require consensus from the majority (51%) of the members of the chain. The information that is provided to the model and the changes within the model can always be traced back to the company that was responsible for it. This feature, in combination with the aspect of blockchain technology that every participant of the network holds a copy of the whole ledger (Morabito, 2017), implies that there a form of social control within the system that will incentivise giving good input. The consequences of reckless behaviour are pinpointed out to the person who behaved recklessly (Tapscott & Tapscott, 2016). Also, the ownership of data can be transferred in a transparent way with a public permissionless blockchain. The blockchain records, for every company that is involved, what information was provided as input; hence, the people responsible for specific information can always be traced.

Access within the material passport is structured according to who has what kind of rights. Within the blockchain, only the adaptions to the data in the material passport are visible. This results in that specific data is only visible to the company that has rights to it within the database. Kembro, et al. (2017) mentioned that when information is shared with many companies, it is difficult to control exactly what information is shared with whom. With the use of the blockchain within the material passport there is always one location which states what information is sent with whom. A requirement that was mentioned in the interviews is that companies which provide good information need to be rewarded for their work. This can be a financial reward or a score that represents good behaviour. Within the blockchain, this can be structured with a native coin.

Lambert (2001) stated that unification of the method of description is indispensable since there is a need to understand the information at every stage of the supply chain and over the lifecycle of a building. The interviewees stated that the implementation of the material passports stimulates uniformity within the market. However, the addition of blockchain technology for material passports does not stimulate further uniformity.

The improved situation was validated by some of the interviewees. Within this validation is controlled if the improved situation adds value above that of the current situation. There came forward that the respondents perceive an added value when blockchain technology is implemented.

For the implementation of material passports, some actors are viewed as more important than others. The owner of a building and the government were named as the most important actors. The owner is seen as an important actor because he or she owns the asset and is responsible for it, and therefore has an incentive to keep the data in good quality. The government was also mentioned often in with regard to regulations. Banks were mentioned as important actors because they give financial incentives for the implementation of material passports.

Management summary (Dutch)

Abstract

De huidige lineaire economie is gebaseerd op het take-make-dispose model. Dit model is gebaseerd op het consumeren van goederen in plaats van het behouden van de hoogste waarde voor materialen. Wanneer dit model het meest dominante model blijft, zal de schaarste van grondstoffen toenemen. Dit zal de kosten en prijsvolatiliteit van deze grondstoffen opdrijven. De lineaire economie veroorzaakt niet alleen problemen met betrekking tot grondstoffen, maar heeft ook een grote impact op het milieu. Het gebruik van producten binnen het take-make-dispose model creëert enorme hoeveelheden afval. Het concept van een circulaire economie minimaliseert deze afvalstromen. Een gebrek aan informatie wordt vaak genoemd als een van de hoofdproblemen dat leidt tot de creatie van afval. De creatie van materiaalpaspoorten kunnen een oplossing bieden voor dit probleem. Er zijn echter nog barrières die het gebruik van materiaalpaspoorten kunnen tegenhouden. Aan de hand van semigestructureerde interviews is geanalyseerd welke kansen, barrières en eisen als essentieel worden beschouwd bij het gebruik van materiaalpaspoorten. Deze kansen, barrières en vereisten worden samengevoegd in een uitgebreide lijst van aspecten die belangrijk zijn voor materiaalpaspoorten. Deze studie brengt de aspecten in beeld die aangepakt kunnen worden door middel van blockchaintechnologie. Uit de uitkomsten kan worden geconcludeerd dat blockchaintechnologie kan worden gebruikt als een validatietool voor een materiaalpaspoort. De openbare permissieloze blockchain kan worden gebruikt om elke invoer van nieuwe informatie en aanpassingen in het materiaalpaspoort te valideren. Dit creëert één waarheid binnen het netwerk welke toegankelijk is voor alle deelnemers. Binnen de blockchain is altijd zichtbaar wie de eigenaar is en wie welke aanpassingen heeft gedaan aan de data. Dit verbeterde scenario is uitgelegd aan de hand van de aspecten van voorziening, opslag, toegang, kwaliteit, presentatie en het proces van het geven van informatie. Naast het beschrijven van belangrijke aspecten van de materiaalpaspoorten worden ook voorstellen gedaan over hoe deze aspecten aangepakt kunnen worden door gebruik te maken van blockchaintechnologie. Daarnaast worden verschillende mogelijkheden voor vervolgonderzoek gepresenteerd.

Tijd voor een nieuw model

De oorsprong van de huidige lineaire economie, het take-make-dispose-model, dateert uit de tijd van de industriële revolutie. De laatste 150 jaar worden gedomineerd door dit lineaire model, waarin goederen worden vervaardigd uit grondstoffen, verkocht, gebruikt en uiteindelijk als afval worden weggegooid (Ellen MacArthur Foundation, 2013a). Door dit patroon voort te zetten zal de schaarste van grondstoffen toenemen. Wanneer de toegang tot nieuwe grondstoffen moeilijker en duurder wordt zal de prijsvolatiliteit alleen maar toenemen (Ellen MacArthur Foundation, 2013a). Dit kan ook het aanbod in de toekomst bedreigen omdat natuurlijke grondstoffen zoals mineralen eindig zijn. Ook zijn veel reserves al erg beperkt (Andrews, 2015; Ellen MacArthur Foundation, 2013). De Nederlandse bebouwde omgeving is voor 90% afhankelijk van grondstoffen zoals ijzer, aluminium, koper, klei, kalksteen en hout (Odijk & Bovene, 2014). De lineaire economie veroorzaakt niet alleen problemen met betrekking tot materiële schaarste, maar dit model heeft ook een grote impact op het milieu. Het gebruik van producten in het take-make-dispose model resulteert in een groeiende hoeveelheid afval. Een deel van dit afval wordt gerecycled maar een groot deel eindigt op de afvalberg. De huidige manier van recycling is daarom niet optimaal en wordt ook wel downcycling genoemd. De teruggewonnen materialen uit recycling zijn vaak van mindere kwaliteit in vergelijking met de originele materialen (Odijk & Bovene, 2014).

Een nieuwe manier van denken

In het laatste decennium stegen de prijzen van de ruwe materialen en is er sprake van grote prijsschommelingen. Deze verandering in de toeleveringsketen maakt de overgang naar een nieuw systeem noodzakelijk (Ellen MacArthur Foundation, 2013a). In een circulaire economie wordt de waarde van producten zo lang mogelijk behouden en wordt afval geëlimineerd. Om het concept van een circulaire economie te implementeren, is een nieuwe manier van denken vereist die de economie opnieuw zal vormen. Het concept van een circulaire economie herdefinieert de wijze waarop de materiaalstromen door de economie bewegen (Prendeville, Cherim en Bocken, 2017). De Ellen MacArthur Foundation (2013a) beschrijft het concept van een circulaire economie als volgt:

> *"Een circulaire economie is herstellend en regeneratief in haar opzet en heeft tot doel producten, componenten en materialen ten allen tijde op haar hoogste waarde te houden. Het concept maakt onderscheid tussen technische en biologische cycli. "*

Een betere toekomst met materiaalpaspoorten

De invoering van meer circulaire bedrijfsmodellen belooft een betere toekomst voor de Europese economie. Het zou Europa in staat stellen om de huidige en toekomstige uitdagingen van mondiale druk op ruwe materialen aan te pakken. Ook zou het de toenemende onzekerheid van het aanbod kunnen verminderen (Europese Commissie, 2014a). De introductie van materiaalpaspoorten is een concrete maatregel welke het hergebruik van materialen kan stimuleren. Dit wordt gedaan door de transparantie te vergroten, een circulaire business case te ontwikkelen en herallocatie van materialen mogelijk te maken. (Circle Economy, 2015). Om de potentiële waarde van circulaire materialen, producten en systemen te begrijpen, is een betrouwbare set van informatie noodzakelijk. Materiaalpaspoorten zijn ontwikkeld met het doel om deze informatie te verstrekken (Luscuere, 2017).

Kansen met blockchaintechnologie

Technologie komt herhaaldelijk naar voren als een belangrijke driver om circulaire lussen mogelijk te maken. Hiermee wordt vraag en aanbod verbonden. De nieuwe technologische doorbraken zullen noodzakelijk zijn om de hoeveelheden data die een circulaire economie nodig heeft, aan te pakken, op te slaan en te beheren (Pomponi & Moncaster, 2017). Blockchaintechnologie biedt kansen om deze grote hoeveelheden data aan te pakken en te structureren. Het verhoogt de transparantie en maakt het mogelijk om informatie over de impact en de herkomst van materialen te ontsluiten (Nederlandse Blockchain Coalitie, 2017). Blockchain is een baanbrekende innovatie omdat voor het eerst in de geschiedenis digitale transacties kunnen worden uitgevoerd zonder afhankelijk te zijn van een tussenpersoon (Ellen MacArthur Foundation, 2017b). Het kan ook worden gebruikt voor het volgen van de authenticiteit en herkomst van zowel digitale als fysieke producten. Dit zou een revolutie teweeg kunnen brengen in supply chain management, toezicht op producten en intellectueel eigendomsbeheer (Bauman, Lindblom, & Olsson, 2016).

Barrières en voorwaarden

Uit het literatuuronderzoek en de interviews is gebleken dat materiaalpaspoorten nog steeds bepaalde barrières moeten overwinnen en voorwaarden moeten vervullen voordat zij op grote schaal kunnen worden geïmplementeerd. De interviews die werden uitgevoerd, waren gestructureerd rondom de verschillende fases van de levenscyclus van een gebouw. Stakeholders uit de fases initiatief, bouw, onderhoud en hergebruik zijn geïnterviewd over hun ervaring met materiaalpaspoorten. Op basis van hun verschillende antwoorden kan worden vastgesteld dat zij materiaalpaspoorten zien als een belangrijk hulpmiddel om hun eigen processen te verbeteren. Uit de interviews blijkt ook dat er momenteel gegevensverlies optreedt tussen de verschillende fasen van de levenscyclus van een gebouw.

De geïnterviewde erkenden dat het materiaalpaspoort een mogelijke oplossing is voor het gegevensverlies dat momenteel optreedt. Aan de hand van de interviews is een lijst gemaakt waar materiaal paspoorten aan moeten voldoen. Voor deze lijst zijn de kansen, barrières en voorwaarden samengevoegd om één volledige lijst te verkrijgen. Deze lijst is gebruikt om te bepalen welke aspecten kunnen worden verbeterd doormiddel van blockchaintechnologie. Een panel van deskundigen werd geraadpleegd om te bepalen welke aspecten kunnen worden verbeterd met behulp van de publieke permissieloze blockchain. De publieke permissieloze blockchain werd gebruikt in dit onderzoek omdat het de mogelijkheden van deze nieuwe technologie illustreert. De volledige lijst van aspecten wordt weergegeven in tabel 2. De aspecten die kunnen worden verbeterd met blockchaintechnologie zijn weergegeven in het zwart.

Table 2: Aspecten materiaalpaspoort gerelateerd aan blockchaintechnologie

Aspects	# Covering code	Supplier	Architect I	Architect II	Advisor	Contractor	Maintainer	Facility manager	Owner	Urban Miner	Recycler	Municipality
Provision of the information	1 Reward system	x	x	x	x				x	x		x
	2 Only necessary information		x			x	x	x		x	x	
	3 Easy handling	x	x					x				
	4 Solving confidentiality	x	x				x					
	5 Cooperation supply chain				x		x					
	6 Data continuity					x			x			
	7 Standardisation of data		x			x						
	8 Predevined levels of detail	x										
Storage of the information	1 Clear ownership data	x	x	x			x		x			x
	2 One data source								x			
	3 Security	x										
Access of the information	1 Predefined who has access	x			x			x	x			
Quality of the information	1 Validation		x	x	x		x	x	x	x	x	
	2 Data management	x			x		x	x	x	x	x	x
	3 Determining real value					x		x	x	x	x	x
	4 Immutable		x	x	x	x	x					
	5 Traceability									x		
	6 Dynamic during the lifetime		x									
Presentation of the information	1 Uniformity	x		x	x	x	x	x	x		x	x
Process of giving information	1 Added value has to be clear	x			x							
	2 Information request at the beginning	x								x		
	3 Experiment								x			

Verbeterd materiaalpaspoort met blockchaintechnologie

In de verbeterde situatie wordt blockchain toegevoegd aan de database waarin de materiaalpaspoorten worden opgeslagen. De verbeterde situatie is zichtbaar in figuur 1.

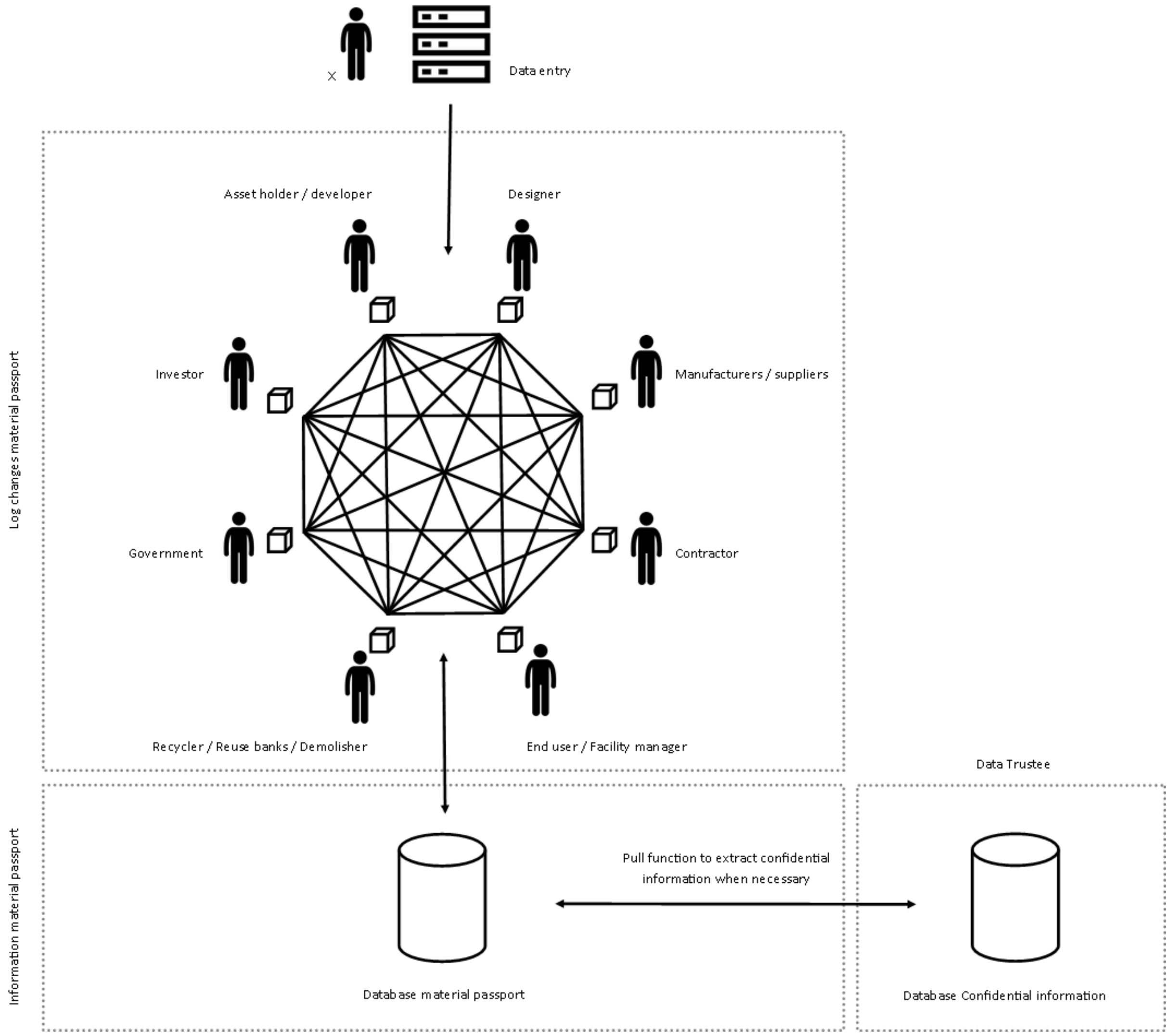

Figure 2: Verbeterde situatie materiaalpaspoort met blockchaintechnologie (eigen illustratie)

In de verbeterde situatie wordt informatie opgeslagen in een database die eigendom is van de eigenaar van het gebouw. De eigenaar blijft verantwoordelijk voor het up-to-date houden van de gegevens. Elk bedrijf is verantwoordelijk voor het verstrekken van zijn eigen informatie aan het materiaalpaspoort, maar de eigenaar van het gebouw is de enige die de motivatie heeft om het materiaalpaspoort in zijn geheel up-to-date te houden. Alle nieuwe informatie die wordt verstrekt aan het materiaalpaspoort en alle aanpassingen worden in de blockchain vastgelegd. Elke deelnemer kan zien wie de eigenaar is en wie verantwoordelijk is voor specifieke gegevens en aanpassingen (Morabito, 2017). Met de blockchain is het mogelijk om één waarheid in het netwerk te creëren, zodat alle bedrijven kunnen controleren of ze over de juiste data beschikken. Wanneer een mutatie wordt geverifieerd en goedgekeurd door de deelnemende knooppunten, is het bijna onmogelijk om de gegevens te wijzigen of aan te passen. Het proces van een aanpassing van de data op de blockchain is moeilijk en vereist overeenstemming van de meerderheid (51%) van de leden van het netwerk. De informatie die aan het model wordt verstrekt en de wijzigingen binnen het model kunnen altijd terug worden getraceerd naar het bedrijf dat er verantwoordelijk voor was. Deze functie, in combinatie met het aspect van blockchaintechnologie dat elke deelnemer van het netwerk een kopie van het hele grootboek heeft (Morabito, 2017), impliceert dat er een sociale controle is in het systeem welke goede invoer zal stimuleren. De gevolgen van roekeloos gedrag zijn terug traceerbaar naar de persoon die zich roekeloos gedroeg (Tapscott & Tapscott, 2016). De betekent een optimale vorm van transparantie. Toegang binnen het materiaalpaspoort is gestructureerd op basis van rechten. Binnen de blockchain zijn alleen de aanpassingen aan de gegevens in het materiaalpaspoort zichtbaar. Dit heeft als resultaat dat specifieke gegevens alleen zichtbaar zijn voor het bedrijf dat de rechten bezit binnen de database. Kembro, et al. (2017) vermeldde dat wanneer informatie met veel bedrijven wordt gedeeld, het moeilijk is om precies te bepalen welke informatie met wie wordt gedeeld. Met het gebruik van de blockchain voor materiaalpaspoorten is er altijd één locatie die aangeeft welke informatie met wie is verzonden. Een belangrijk punt dat in de interviews werd genoemd, is dat bedrijven die goede informatie verstrekken, voor hun werk beloond moeten worden. Dit kan een financiële beloning zijn of een score welke goed gedrag vertegenwoordigt. Binnen de blockchain kan dit worden gestructureerd met een eigen munt.

Lambert (2001) verklaarde dat uniformiteit van de beschrijvingsmethode belangrijk is omdat de informatie in elke fase van de levenscyclus van een gebouw begrepen moet worden. De geïnterviewde verklaarden dat de implementatie van de materiaalpaspoorten deze uniformiteit zal stimuleren. De toevoeging van blockchaintechnologie stimuleert deze uniformiteit niet extra.

De verbeterde situatie is gevalideerd door enkele geïnterviewde bedrijven. Binnen deze validatie werd gecontroleerd of de verbeterde situatie waarde toevoegt in vergelijking met de huidige situatie. Er kwam naar voren dat de geïnterviewde een toegevoegde waarde zien wanneer blockchaintechnologie wordt geïmplementeerd.

Voor de implementatie van materiaalpaspoorten worden sommige actoren als belangrijker ervaren dan anderen. De eigenaar van een gebouw en de overheid werden genoemd als de belangrijkste actoren. De eigenaar wordt gezien als een belangrijke actor omdat hij als enige motivatie heeft om de gegevens in het paspoort up-to-date te houden. De overheid werd ook vaak genoemd met betrekking tot regelgeving rondom het invoeren van de paspoorten. Banken werden genoemd als belangrijke actor omdat ze een financiële prikkel kunnen geven voor de implementatie van materiaalpaspoorten.

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1. Introduction

This chapter illustrates the starting point of the research and introduces the research topic. First it elaborates on the research objective, followed by a problem analysis. After this, the research questions, scientific relevance, and practical relevance of the study area is discussed.

1.1 Background

The origins of the current linear economy, the take-make-dispose model, date back to the industrial revolution. The current global economy is based on this model (Andrews, 2015). The last 150 years of industrial evolution have been dominated by this linear model in which goods are manufactured from raw materials, sold, used, and finally thrown away as waste (Ellen MacArthur Foundation, 2013a). This system in combination with global trade has resulted in enormous economic growth and improved human welfare (The Circle Economy, IMSA, 2013). However, continuing this pattern will increase the scarcity of raw materials, which will drive up input costs and price volatility when the access to new raw materials becomes more challenging and expensive (Ellen MacArthur Foundation, 2013a). Material scarcity will increase when the world population grows in the near future. The current population of 7,3 billion people is expected to grow to 8,5 billion by 2030, 9,7 billion by 2050, and 11,2 billion by 2100 (United Nations, 2015). In more detail, up to 3 billion more middle-class consumers will emerge in the next 20 years compared to the 1,8 billion consumers of 2014. In addition, by 2050 it is expected that 66% of the world population will live in urban areas, compared to 54% in 2014 (United Nations, 2014).

The growing number of consumers will drive up the demand for a range of different resources and materials (Dobbs, Oppenheim, Thompson, Brinkman, & Zornes, 2011). This could threaten supply in the future, because natural raw materials, such as minerals, are finite and many reserves are already very limited (Andrews, 2015; Ellen MacArthur Foundation, 2013). It is predicted that by 2030 83 billion tons of minerals, metals, and biomass will be extracted from the earth, this is 55% more than in 2010 (Boer & Bergen, 2012). A second result of the rising demand is that supply security may decrease for certain raw materials, this can affect the Dutch economy. In addition, certain materials are sourced only from a few countries, which can cause geopolitical tensions. If markets fail to work properly, the supply of raw materials can stockpile (Bastein & Rietveld, 2015). The Dutch economy imports 68% of its raw materials, and the whole economy is dependent on these material flows (Ministry of Economic Affairs, 2016). In the 1990s, the built environment was responsible for 30% of the energy and 40% of the materials consumed globally. Nowadays, the construction sector remains the largest consumer of raw materials, and is responsible for 25% to 40% of global carbon dioxide emissions (Pomponi & Moncaster, 2017). The Dutch built environment is 90% dependent on raw materials like iron, aluminium, copper, clay, limestone, and wood (Odijk & Bovene, 2014).

A linear economy not only creates problems regarding material scarcity, it also results in environmental degradation. The use of products in the take-make-dispose model results in large amounts of waste. Some waste is recycled but a most is assigned as landfill. The current way of recycling is suboptimal and is referred to as downcycling. The recovered materials from recycling are of less quality than the original materials (Odijk & Bovene, 2014). In recycling, not all the materials in products can be saved and many valuable materials leak away from the economy (European Commission, 2014a). Information about materials may be scattered or unavailable and this is a main contributor in the creation of waste (Debacker & Manshoven, 2016). The construction sector produces an enormous amount of waste. A small improvement in the recovery of raw materials can offer huge potential benefits in this sector. Currently about 40% of the solid waste in our economy derives from construction and demolition work (World Economic Forum, 2016).

Attention to the problems that occur by using natural resources is not new. In 1972, the Club of Rome published a book called 'Limits to Growth' (1972). The book raised awareness of ecological limits related to economic and demographic growth in combination with available natural resources and raw materials. The Brundtlandt Commission (1987) published a report which indicated that there was a need for a model to achieve sustainable development. Different concepts have been proposed in recent decades, with some examples being the cradle-to-cradle model (McDonough & Braungart, 2002), performance economy (Stahel, 2006), biomimicry (Benyus, 1998), blue economy (Pauli, 2012), regenerative design (Lyle, 1994), and the natural step (The Natural Step, 2017). The concept of a circular economy is gaining momentum and its origins are these different schools of thought.

In the last decade, the prices of natural resources increased and became more volatile. This change in the supply chain makes the change to a new system necessary (Ellen MacArthur Foundation, 2013a). In a circular economy, the added value of products is kept for as long as possible and the waste is eliminated. The resources are kept within the economy when a product has reached the end of its lifecycle but can be used productively again, and hence can create further value (European Commission, 2014a).

To really integrate the concept of a circular economy, a new way of thinking is needed that will reshape the economy. The paradigm of a circular economy is gaining momentum and promises to balance environmental and economic prosperity (Pomponi & Moncaster, 2017). The concept of a circular economy re-imagines how material flows that move through economies might be closed (Prendeville, Cherim, & Bocken, 2017). The Ellen MacArthur Foundation (2013a) describes the concept of a circular economy as follows:

> *"A 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. The concept distinguishes between technical and biological cycles."*

Moving to more circular business models promises a brighter future for the European economy. It would allow Europe to rise to the challenge of global pressure on resources and insecurity of supply (European Commission, 2014a). The European Union would gain more than 1,8 trillion euros if a circular economy was implemented (Ellen MacArthur Foundation, 2015). The Dutch government wants the national economy to use only reusable raw materials by 2050. One intermediate goal is a 50% decrease in the use of primary raw materials by 2030 compared to 2012 (Kubbinga, et al., 2017). TNO (2013) estimated that the Dutch economy would grow by 7,3 billion euros by 2020 if circular economy principles were implemented, resulting in 54.000 new jobs.

The introduction of material passports is a concrete measure that can be of great help in stimulating the reuse of materials, through increasing transparency to develop a circular business case and enabling the reallocation of materials (Circle Economy, 2015). A material passport gives a representation of all the materials that are included in a building. To understand the potential value of circular materials, products, and systems, a reliable set of information is necessary. Material passports are created with the aim of providing such information (Luscuere, 2017).

The exponential growth of digital connectivity has had a great impact on society in the last decade. The increase in connectivity and technical innovation can create important sources of value for citizens and economies. This revolution is called the 'Fourth Industrial Revolution' and will strongly influence how a circular economy is implemented (Ellen MacArthur Foundation, 2017b). Technology repeatedly emerges as a key aspect to enable circular loops to connect demand and supply, and to handle, store, and manage the huge amount of data that a circular economy requires (Pomponi & Moncaster, 2017).

Blockchain technology offers opportunities for new social processes. It has the potential to bring a circular economy closer, enable the sub-economy, increase transparency, facilitate information on carbon footprints and the origin of material. It can enhance citizens' autonomy and privacy as well as cyber-security, and could lead to revolutionary forms of enterprise planning and control (Dutch Blockchain Coalition, 2017). Blockchain is a game-changing innovation because for the first time in history, digital transactions can be made without having to rely on an intermediary (Ellen MacArthur Foundation, 2017b). The intermediary was always the trusted person within transactions. Blockchain technology creates a trusted environment through its transparent nature. It makes information available for the entire network, while assuring the integrity and immutability of data (Seebacher & Schüritz, 2017). It can also be used for immutable tracking of authenticity and provenance of both digital and physical products, these features could revolutionize supply chain management, regulatory oversight, and intellectual property management (Bauman, Lindblom, & Olsson, 2016).

1.2 Problem definition

A key recommendation in the report 'Growth Within: A Circular Economy Vision for a Competitive Europe' (2015) was to develop a material backbone, a system to optimize the circulation of materials and minimize the need for new raw materials. Using such a system, Europe can strengthen its competitiveness. A system like this contains much data that will need to be structured properly. The Ellen MacArthur Foundation (2017b) added to this vision that in particular asset-tracking solutions could play a key role. The lack of exchange of information is consistently cited as a constraint for the success of circular initiatives (Winans, Kendall, & Deng, 2017). Verberne (2016) endorsed this point by saying that due to the complexity and increase of big data within the built environment, an information management system should be embraced or developed that can keep track of all the materials with their characteristics. Important aspects of such a system are confidentiality and trust, because these issues could hamper the exchange of information. Confidentiality issues are one of the biggest barriers for the implementation of material passports (Damen, 2012). The sharing of information within the supply chain may encounter challenges, such as the confidentiality of shared information, incentive issues, reliability and costs of the information management system, anti-trust regulations, the accuracy of shared information, and possibilities that would allow companies to utilize shared information effectively (Lotfi, Mukhtar, Sahran, & Taei Zadeh, 2013). At present no system exists that can overcome all these barriers. However, blockchain technology shows good potential to facilitate storage and sharing of the information within material passports. Distributed ledgers can become the foundation of a robust system of trust and a decentralized platform for massive collaboration. With this system, intermediaries would be removed and assets that once were dormant can be exploited (Brill, et al., 2016).

1.3 Research question

The main objective of this thesis is to investigate how blockchain technology can add value to the implementation of material passports. To achieve this objective, there is explored how a circular supply chain in the construction sector shares information from material passports. Barriers that prevent the sharing of information from material passports in the supply chain of the Dutch construction industry were investigated. As described in the problem definition, trust issues can be a challenge that prevents the implementation of material passports. In addition, the requirements for sharing information are analysed. For innovations, it is important that the benefits are clear for various stakeholders in order to get a successful and wide implementation. Therefore, the benefits of blockchain technology are investigated and how this technology might be suitable for overcoming these barriers. This results in the overall aim of this research to show how the construction sector can use blockchain technology to innovate the process of sharing information from material passports by taking away the barriers and fulfil the requirements.

Main research-question

To what extent can blockchain technology be used to improve the implementation of material passports in the circular built environment?

Sub research-questions

Circular Economy

- What is a circular economy?
- What does a circular economy mean for the built environment?
- What is a material passport and, what kind of information is stored in these passports?

Blockchain

- What is blockchain technology and how does it work?
- What are the opportunities for blockchain technology to improve material passports?

Based on the literature study and the interviews, the following questions were be answered:

- What are the barriers to sharing information from material passports?
- What are the requirements for data that are taken from a material passport, before such data can be used by the different users?
- How can blockchain technology remove the barriers or fulfil the requirements?
- Who are the most important actors in relation to the implementation of material passports?

1.4 Scientific relevance

Blockchain technology is expected to revolutionize various potential areas of application. The expectations for this technology are high, but the real-world impact and benefits remain unclear (Seebacher & Schüritz, 2017). Yi-Huumo et al. (2016) reviewed all research to date that has been executed within the blockchain area. The results showed that over 80% of the papers were based on Bitcoin and less than 20% dealt with blockchain technology and its possible applications. Most of the research has focused on identifying and improving the limitations of the blockchain from the perspective of privacy and security. Among the 20% the papers that dealt with other blockchain applications, hardly any scientific research has been conducted on the possibilities of blockchain within the built environment. With the growing interest in this topic, the lack of scientific research shows a need for understanding the possibilities of blockchain technology are explored within the built environment. The current study attempts to fill this knowledge gap.

1.5 Practical relevance

The word 'blockchain' is one of the most hyped words that has emerged in last couple years. Currently, blockchain finds its way into the media headlines almost daily, whereas a couple of years ago it was of interest only by relatively small number of enthusiasts (Morabito, 2017). Blockchain receives more and more attention in public discussion and in the media. Some enthusiasts claim that blockchain technology is the biggest invention since the appearance of the internet (Drescher, 2017). Blockchain is a young digital technology which creates a new dimension of digital trust. The technique is in its initial phase, so its full potential still needs to be discovered. The social, economic, technical, and legal expertise in this area is still limited, both within specialized companies and within knowledge-based and scientific institutions (Dutch Blockchain Coalition, 2017).

Clearly, more companies, researchers, and governments are interested in the potential impact of blockchain technology on society. With all this attention, blockchain has also captured the interest of everyday citizens. Figure 3 shows the Google searches on 'blockchain' in recent years.

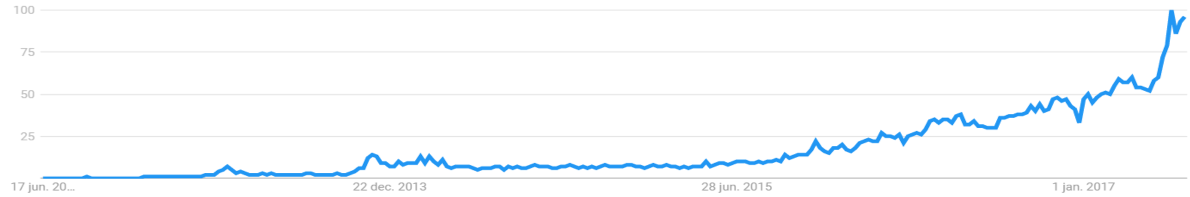


Figure 3: Google searches on blockchain (Google, 2017)

A technique that has the potential to change how business is done is worthy of investigation. As described in a previous section, blockchain indeed does have the potential to improve how a circular economy is implemented in the built environment.

This research contributes to understanding the possibilities for blockchain technology within the research area. It defines a starting point from which companies or research institutions in the field of the built environment can build on blockchain applications.

1.6 Research design

Because of the explorative nature of this research, the framework of Hevner, March, and Park (2004) was used to structure the research process. This framework is helpful when conducting and evaluating a design research for an information system. This framework, shown in figure 4, is widely used for improving information systems. The framework emphasizes the connection between a circular economy and blockchain technology. Various validation or feedback loops ensure that the conclusions of this research will fit on the current findings within this domain.

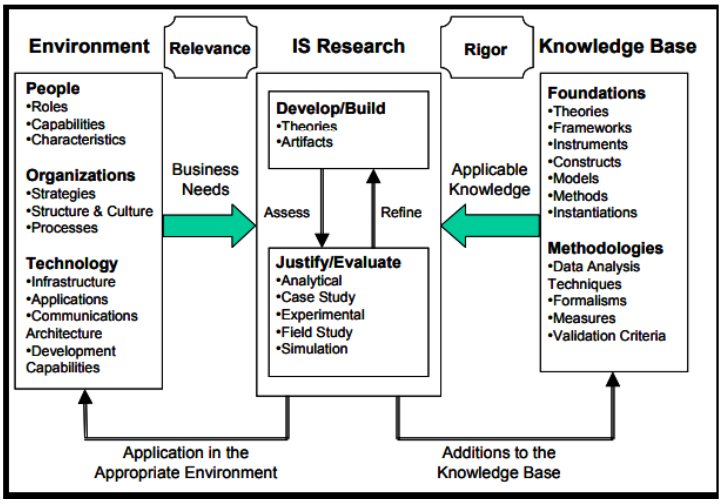


Figure 4: Framework information systems research (Hevner, March, & Park, 2004)

Figure 4 shows an overview of the four different phases of this research. This research framework is based on the framework of Hevner, March, and Park (2004). The different steps describe the different phases of this research. In step 1 of figure 4 the literature review is conducted. To acquaint yourself with the available existing knowledge about the research topic a literature review is necessary. A well-executed literature review can bring focus to the problem definition, improves the methodology, broaden the knowledge base of the researcher, and creates a context for the findings (Kumar, 2011). The literature review is the important foundation for the whole research. The literature review will clarify the two major concepts of this study, namely a circular economy with material passports and blockchain technology.

Circular economy

The literature review related to circular economy clarified this type of economy within the built environment. For this framework, the concept of a circular economy as proposed by the Ellen MacArthur Foundation (2013a) was used. It illustrates the usage of a material passport over the lifetime of a building. In addition, the theoretical framework included the different stakeholders that are involved in using the material passport.

Blockchain

The literature review about blockchain technology clarified the concept and focused on how this technology works. The information helped identifying opportunities where this technology can support a circular economy with material passports. Due to the scope of this research, there is focussed on how the public permissionless blockchain can improve the concept of material passports. Also the programming aspect of blockchain technology is not examined here. As mentioned earlier, the scientific literature on blockchain technology is limited. This study reviewed the findings of different studies to create a clear framework which was used as a basis the interviews and expert panel.

In Step 2 (figure 5), the individual semi-structured in-depth interviews were conducted. The reason for this type of data collection is described in Chapter 4. The interviews were structured around a case study of the CIRCL pavilion – a circular pavilion built by ABN AMRO. The interview data were used to validate the use of material passports, as described in the theoretical framework, and to identify barriers that actors encounter when using these passports. The requirements for material passports were also analysed. This provided the knowledge base according to the framework of Hevner, March, and Park (2004) (figure 4) that defined the problem space in which this research was conducted.

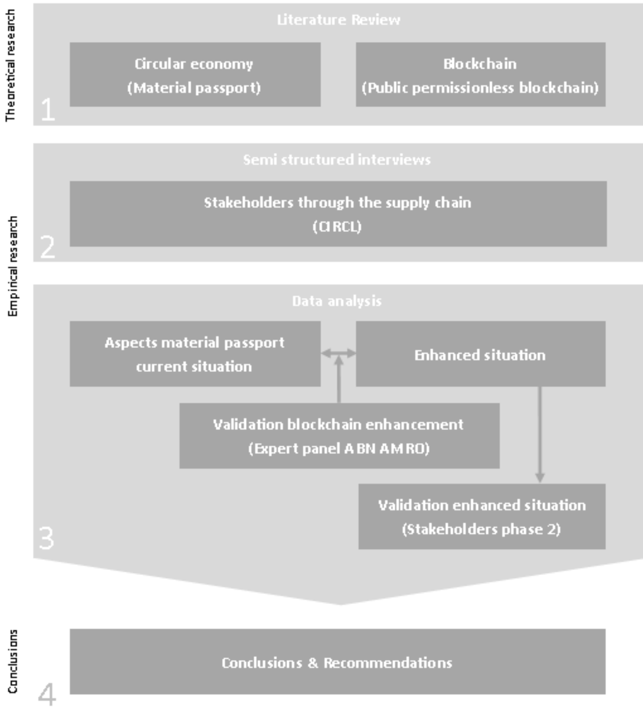


Figure 5: Research design (own illustration)

In Step 3 (figure 5), the results from the interviews were analysed. In this phase, an analysis of whether the characteristics of blockchain technology contribute to removing these barriers or fulfilling the requirements was conducted. The results were validated in an expert session with blockchain professionals. In this expert session, the question 'Can blockchain really take down the proposed barriers or fulfil the proposed requirements?' was discussed. With the results from this expert panel, a desired situation was created in the form of an artefact. This is a visual representation of the proposed concept. The scenario was then validated by certain interviewees. The validation confirmed whether the enhanced material passport was an improvement compared to the current situation. In this step, the develop and build phase and the justify and evaluate phase occurred according of the framework from Hevner, March, and Park (2004) (figure 4).

Step 4 (figure 5) was focussed on writing down the conclusions and identifying areas for further research. The conclusions of this research were reflected upon in this phase.

1.7 Thesis layout

The structure of the thesis is shown in figure 6, and the chapters are summarized below.

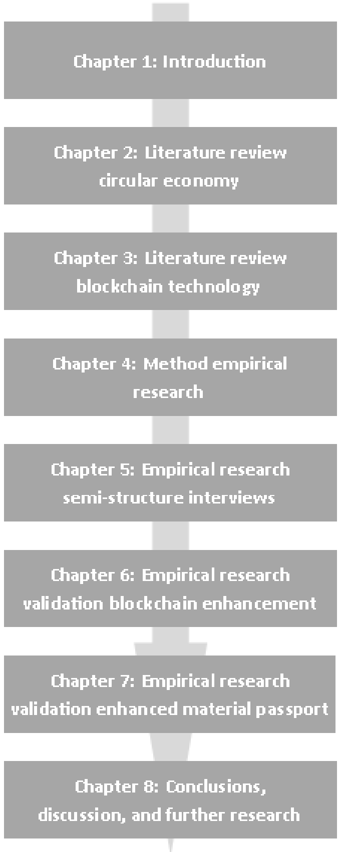


illustration)

Chapter 1: Introduction

In this chapter, the topic has been introduced, including the context of the problem. This led to the research questions and the theoretical and practical relevance, followed by an outline of the research method, the structure, and planning of the thesis.

Chapter 2: Literature review: Circular economy

The literature review of a circular economy clarifies the concept of a circular economy in detail. Chapter 2 illustrates a circular economy in the built environment and the concept of material passports.

Chapter 3: Literature review: Blockchain technology

The theoretical framework about the concept of blockchain explains the concept in an easy way. It focuses on describing this technology to identify the opportunities where it can improve the concept of material passports.

Chapter 4: Method empirical research

In chapter 4, the research method is described further. The participants in the interviews, and the interview guide, are explained in this chapter.

Chapter 5: Empirical research: Semi-structured interviews

Chapter 5 shows the results from the interviews. This chapter gives insight into what aspects are necessary for material passports, according the interviewees.

Chapter 6: Empirical research: Validation blockchain enhancement

In this chapter an optimized situation is described where blockchain technology enhances the concept of material passports.

Chapter 7: Empirical research: Validation enhanced material passport

In this chapter, the enhanced material passport with blockchain technology is validated by certain interviewees. With this validation is controlled whether the enhanced material passport adds value compared to the current situation.

Chapter 8: Conclusion, discussion, and further research

In the final chapter, answers to the research questions are presented. Based on these answers, recommendations for further research are presented. The outcomes of this research are reflected in the discussion.

2. Literature review: Circular economy

This section aims to provide a framework on a circular economy in order to understand the working mechanism, key aspects, and main applications. The impact of a circular economy on the build environment will be explained. Finally, material passports will be explained in depth which will be used as input for the interviews.

2.1 Definition of a circular economy

A circular economy is an answer to the problems that were mentioned about the current linear economy in chapter 1. Global trends like resource scarcity, social unrest, volatile market prices, environmental pollution, and rising temperatures are causing the need for a circular economy. In this economy the growth is decoupled from the use of scarce resources through disruptive business models and technology based on renewability, reuse, refurbishment, upgrade, repair, capacity sharing, and decentralization. Companies are no longer focused mainly on squeezing out costs through efficiency in supply chains. They concentrate on rethinking products and services from bottom up to future proof (Accenture, 2014). Currently the subject circular economy is attracting more and more momentum because of the current attention about resource scarcity in combination with the growing demand of materials resulting in price volatility. Also the waste creation in the linear economy is getting more attention. The concept about a circular economy came not from nowhere. It is a combination of the principles of various schools of thought. Key elements of a circular economy are based on various concepts regarding sustainability. The elements are based on the following schools of thought:

Table 3: Different schools of thought

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.

The concept of a circular economy has deep-rooted origins and cannot be traced back to one specific school of thought. The previous mentioned schools of thought have had all influences in the origination of the circular concept. The concept of a circular economy has gained momentum since the late 1970s, led by a small number of academics, businesses, and thought leaders (Ellen MacArthur Foundation, n.d.). The Ellen MacArthur foundation was formed back in 2010 to inspire an entire generation to rethink, redesign, and build a positive future. The foundation believes that a circular economy provides a framework for redesigning the future. Many authors refer to the Ellen MacArthur Foundation report when defining the concept of a circular economy.

2.2 Principles of a circular economy

The interpretation of a circular economy is of substantial interest for the research. Therefore, it is necessary to examine most important principles. Below the principles of the Ellen MacArthur Foundation (2013b) are presented.

- **Design out waste:** Waste does not exist when the technological and biological components of a product are designed with the intention to fit within a material cycle, they need to be designed for easy refurbishment and disassembly. The biological nutrients are non-toxic and can be composted and given back to the nature. The technical nutrients, polymers, alloys, and other man made materials are designed and engineered in such way that they can be used over and over again with minimal quality loss. Joustra, de Jong & Engelaer (2013) emphasizes that a second life of a product within this principle is through a secondary market, recycling, or with its essential parts or materials;
- **Build resilience through diversity:** Modularity, versatility, and adaptively are features that need to be prioritized in this uncertain and fast changing world. Products need to be designed in such way that they can adapt to the changing conditions;
- **Rely on energy from renewable sources:** Systems should the ultimately designed to run on renewable resources. Every circular concept should start by looking into the energy that is involved in the production process. Infinite energy sources like sunlight, biomass, or wind do not harm the environment and need therefore be used for mining, producing, using, and reusing of materials. Joustra, de Jong & Engelaer (2013) describe that especially the recovery and remanufacturing of materials depends on the availability of energy in two forms: physical energy from renewable energy sources and labour;
- **Think in 'systems':** Understanding how parts influence one another within the whole system and the relationship of the whole system to the parts is crucial, not only in place but also in time. Elements are considered within the relationship with their infrastructure, environment, and social contexts. It is focussed on the connection over time and has the potential to create regenerative conditions rather than to only limit its focus on a short term. The whole system loses its essential properties when it is taken apart. The feedback loops in the system provide producers with information about products and resources. Next to the material and nutrient loops, there are also loops of responsibility. These loops provide the producer information about the quality of re-using or recycling of high quality products and resources. The responsible feedback loops provide the producer with a higher level of responsibility for the care of not only the products, but also for the parts of this care (Joustra, de Jong, & Engelaer, 2013);
- **Waste is food:** The value creation within the biological nutrient side lies in the opportunity to create additional value from products and materials by reintroducing them back into the biosphere through non-toxic restorative loops. The value creation on the technical nutrient side is based on converting them into new materials with more value, this is called upcycling.

The five principles describe the idea behind a circular economy. The main objective of a circular economy is that it adds value towards social, environmental and economic aspects in such way that it decreases the demand for raw materials and that it make use of renewable energy sources to decrease its footprint.

2.3 Closing the loop

The Ellen MacArthur Foundation (2013b) presents in their report 'Towards a Circular Economy' a schematic representation of their interpretation of a circular economy. The starting point of the scheme is the reusability of products and raw materials, the restorative ability of natural resources and minimizing waste.

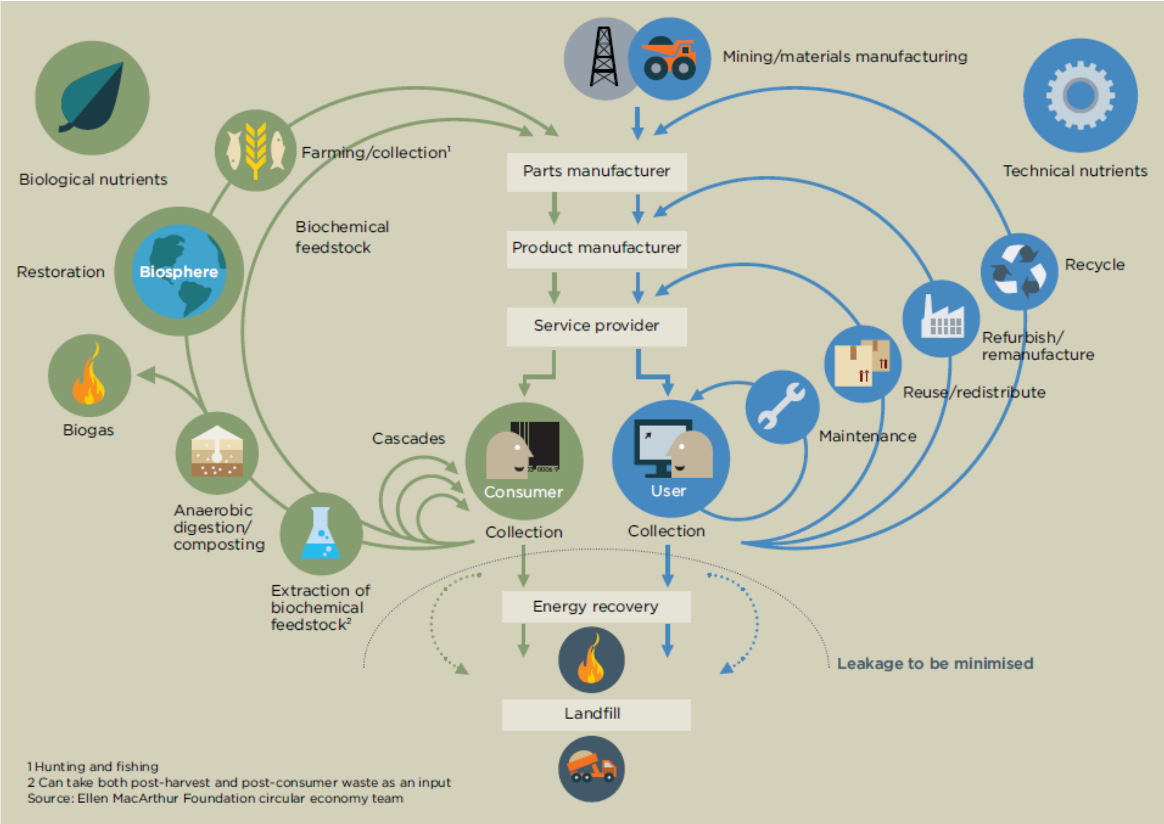


Figure 7: Diagram circular economy (Ellen MacArthur Foundation, 2013b)

In figure 7 the Ellen MacArthur foundation (2013b) makes a distinction between the biological and technical cycles. Biological cycles are based on non-toxic materials that are restored in the biosphere while rebuilding natural capital after being cascaded into different applications. The technical cycles are based on products, components, and materials that are restored into the market at the highest possible quality and for long as possible through repair, maintenance, refurbishment, reuse, remanufacture, and finally recycling. In general it can be concluded that the smaller the circles are, the larger the savings are in the embedded costs of materials, labour, energy, capital, and emissions like greenhouse-gasses. The central vertical axis shows the linear production process. In addition to this linear process the circular arrows show all potential circular loops and minimize the leakage of waste. To stimulate the circular feedback loops the management and exchange of resource related information, end-of-life systems for the flows of resources, products, and networks based on material exchange and networks of collection are needed (Damen, 2012). The system involves careful management of material flows. Transforming towards a circular economy have a direct effect on our production processes and development of a take back system (Ellen MacArthur Foundation, 2013b).

2.4 Circular economy in the built environment

Cities will play a profound role in the transitioning to a circular economy as increasing urbanisation is expected in the coming years. Cities have a high concentration of resources, capital, data, and talent within a small territory, which places them uniquely for this transition. Reverse logistics and material collection could be more efficient due to the geographical focus of the area. This creates more opportunities for reuse and collection based business models (Ellen Macarthur Foundation, 2017a).

The Ellen MacArthur Foundation (2017a) describes the principles of a circular city as an economy on itself that establishes an urban system that is regenerative, accessible, and abundant by design. Circular cities aim to eliminate the concept of waste, keeping assets at their highest value at all times, and are enabled by digital technology. Circular cities stimulate local value loops. This is expressed in more focus on local production and increased and more diverse exchanges in value of products. The following aspects are included:

- **Maker labs** to encourage local production, repair, and distributive manufacturing;
- **Collective resource banks** to even out the demand and supply of materials;
- **Information networks** that stimulate the exchange of goods, materials and services.

The building sector puts a major pressure on the natural environment. The role of the building sector is therefore fundamental in the transition to a circular economy. Current research about a circular economy tends to focus ether on the macro-scale such as eco-parks or micro-scale such as products, with the risk of ignoring the impacts an potential of the meso-scale of individual buildings, visible in figure 8 (Pomponi & Moncaster, 2017).

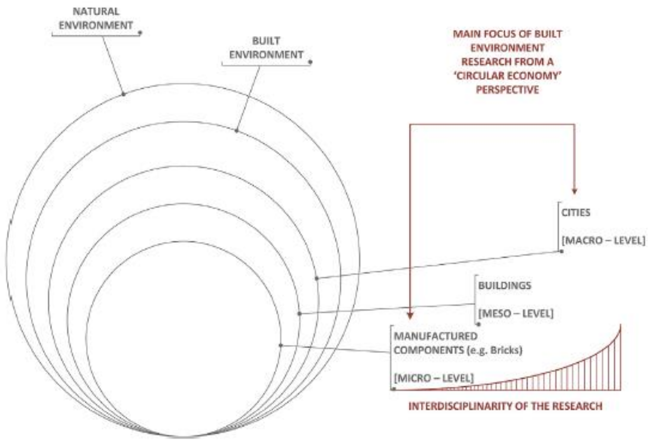


Figure 8: Framing of the built environment (Pomponi & Moncaster, 2017)

The building sector is unique compared to other sectors that are transitioning towards a circular economy. This is not only due to the complexity of buildings, but this is also based on other factors like the long lifetime of buildings (Khasreen, Banfill, & Menzies, 2009). They often exist longer than 50 years and it is difficult to predict their whole lifetime during their development. Because of this long lifespan, buildings can undergo many changes in their form and function. Also many of the environmental impacts of buildings do not occur during their development but during their use. Proper design and material selection are critical to minimize these in-use environmental impacts. At last the building sector is a sector with many stakeholders. For example the designer that makes the decision about the final building is not responsible for the production of the components or the building process. Finally, there is very little standardization, every building is unique in its own way. New choices have to be made for each specific situation (Pomponi & Moncaster, 2017; Khasreen, Banfill, & Menzies, 2009). Considering the average lifetime for construction products to be around 50 years, a significant increase in waste generation is to be expected within the next decades. The only way to respond to this challenge of waste generation can be the consequent increase of recycling rates. For higher recycling rates it is important to have detailed information about the composition of construction waste. The recyclability changes over time, it is a function of technological development and resource markets (Kovacic, Honic, & Rechberger, 2017). Circular building concepts will imply radical changes for the construction sector. It has put forward the idea of 'buildings as material banks', this radically changes the way of how material flows need to be managed. A material bank is a temporary storage of materials that compromise the building. The notion of material banks sheds new light on the value of building materials and products and how to maintain and restore these (Geldermans, 2016). Through design and circular value chains, materials in buildings can maintain their value. An outcome of this is that the sector produces less waste and uses less virgin resources. Buildings will conserve the value and functionality of materials so the materials and building components can be reused and therefore decrease the need for primary resource mining (van Sante, 2017; Debacker & Manshoven, 2016). A certain level of standardization is inevitable in the a circular building industry. It will ensure that materials and products can be reused multiple times without significant adjustments. Standardization of connections is found to be key, particular dry connections are in the infill domain (Geldermans, 2016; Debacker & Manshoven, 2016).

2.4.1 Decomposition of a building

The notion of a building as one object is still very much the dominant way of thinking. However, a building can be decomposed in different layers. Buildings are conceived, designed, constructed, and used as entities. Buildings are constantly being adapted to changing user needs and environment conditions. For those reasons buildings should be seen as dynamic structures that are constantly adapting to the needs of the user (Beurskens & Bakx, 2015). Brand (1994) made the model 'Shearing Layers' that is based on the decomposition of a building. The model is based on the concept that a building is composed from components and materials with different lifetimes. This results in different replacement rates of different components. This is visible in figure 9.

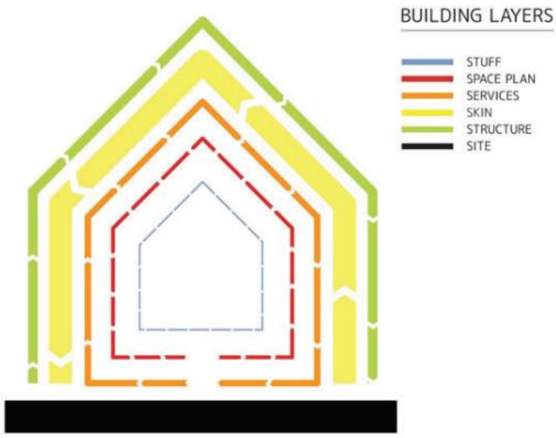


Figure 9: Model shearing layers (Brand, 1994)

- **Site:** The geographical setting, the urban location, and the legally defined lot (eternal);
- **Structure:** The foundation and load bearing elements (30 – 300 years);
- **Skin:** Exterior surfaces (20 years);
- **Services:** Installations (7 – 15 years);
- **Space plan:** Walls, ceilings, floors, etc. (3 – 30 years);
- **Stuff:** Chairs, desks, lamps, etc. (< 1 year).

Lifespan plays a central role in the tension between buildings and the changing environment. The lifespan of a building or a part of a building is therefore not a definite understanding. Each building has a technical, aesthetic, and an economic lifespan. These different types of lifespan differ in length and cycle (SenterNovem, 2007).

- **Technical lifespan:** The period in which the building meets its technical requirements;
- **Functional lifespan:** The period in which the building meets its user requirements;
- **Aesthetic lifespan:** The period in which the building meets the requirements and wishes to the appearance of the building and the environment;
- **Economic lifespan:** The period in which the future earnings are higher than the future costs. The operational phase of a building is after this period no longer economic viable.

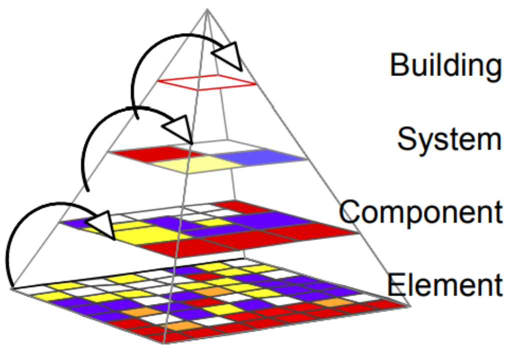


Figure 10: Hierarchy of material levels (Durmisevic & Brouwer, 2006)

From a technical point of view a building can be seen as a hierarchy of material levels which should be described at any level of abstraction. The higher levels in this hierarchy dominate the lower levels of technical composition. The perception of a building as one static product is misleading (Durmisevic & Brouwer, 2006). In figure 10 is this structure visible.

- **Building level** represents the composition of systems which are carriers of the main building functions like load-bearing, enclosure and partitioning;

- **System level** represents the composition of systems which are carriers of the main building functions like bearing, finishing and insulation;
- **Component level** represents the layered or frame assembly of component functions which are allocated through elements and materials at the lowest level of the building assembly (Durmisevic & Brouwer, 2006).

2.4.2 Lifecycle of a building

The current construction and real estate process is not only strongly fragmented, but also follows a long linear chain. In order to make a circular economy function, that linear process must be turned (Kubbinga, et al., 2017). The lifecycle of a building can be divided into four parts. These are the design, build, use & operate, and repurpose & demolition (Pomponi & Moncaster, 2016; Debacker & Manshoven, 2016; Leising, 2016). In figure 11 it is visible how the linear lifecycle of a building is turned into a circular lifecycle. Debacker and Manshoven (2016) described the different phases of the lifecycle as follows:

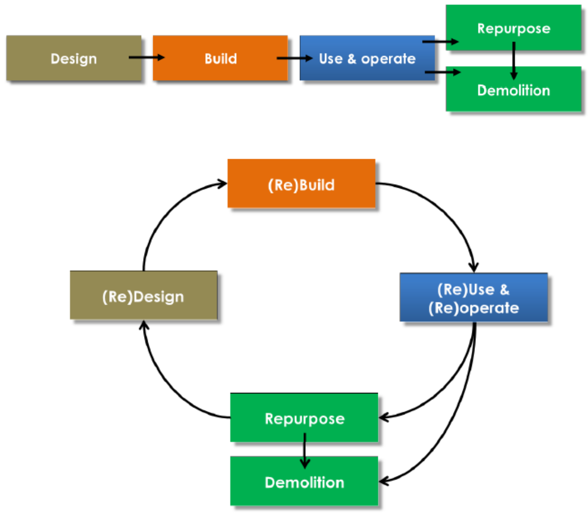


Figure 11: Lifecycle stages of a building linear and circular (Debacker & Manshoven, 2016)

- **Design:** The phase where all the designing, financing, and planning is specified;
- **Build:** The phase where the building is realized;
- **Use & operate:** The phase where users are using the building and the building is operated to maintain the service levels required by the users;
- **Repurpose & demolition:** The phase where the transformation is planned. In the current process not many products and materials are extracted and used again, buildings are the most of the time completely demolished. Within the circular lifecycle this flow of materials are the input for new designs.

Pomponi & Moncaster (2016) added to every part of the lifecycle of a building, the processes that have influence on the environment. A circular economy as presented in the diagram of the Ellen MacArthur Foundation (2013b) is placed over the lifetime of a building. This is visible in figure 12.

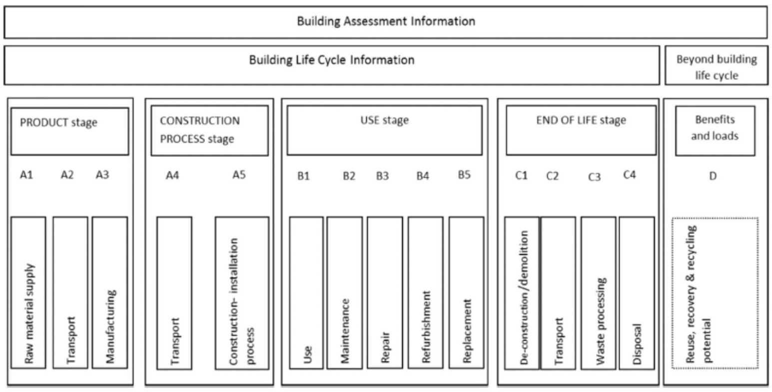


Figure 12: Lifecycle stages of a building (Pomponi & Moncaster, 2016)

2.4.3 Actors during the lifecycle of a building

Identifying stakeholders within the building sector is important as they can change the system with their influence on the supply chain and other stakeholders. Understanding the influence of stakeholders and their interests give relevant insights into how stakeholders can be mobilized for a transition towards a circular economy (Ellen MacArthur Foundation, 2014). A circular supply chain requires that all stakeholders contribute towards an outcome that achieve the best value for all parties, using materials that keep the highest value throughout its lifecycle, and minimize the leakage of waste. Developing integrated value chains could give companies a competitive advantage over time (Carra & Magdani, 2017). Within the building sector the following actors can be distinguished (table 4): investors, asset holder / developers, designers, manufactures / suppliers, contractors, end users / facility managers, recyclers / reuse banks / material extractors, and the government (Carra & Magdani, 2017; van Sante, 2017; Leising, 2016; Vrijhoef & Koskela, 2000).

Table 4: Actors lifecycle building

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).

With this information the following playing field can be visualised. This playing field is visible in figure 13. In this figure the core actors of the building process are divided from the other actors that have influence on the process.

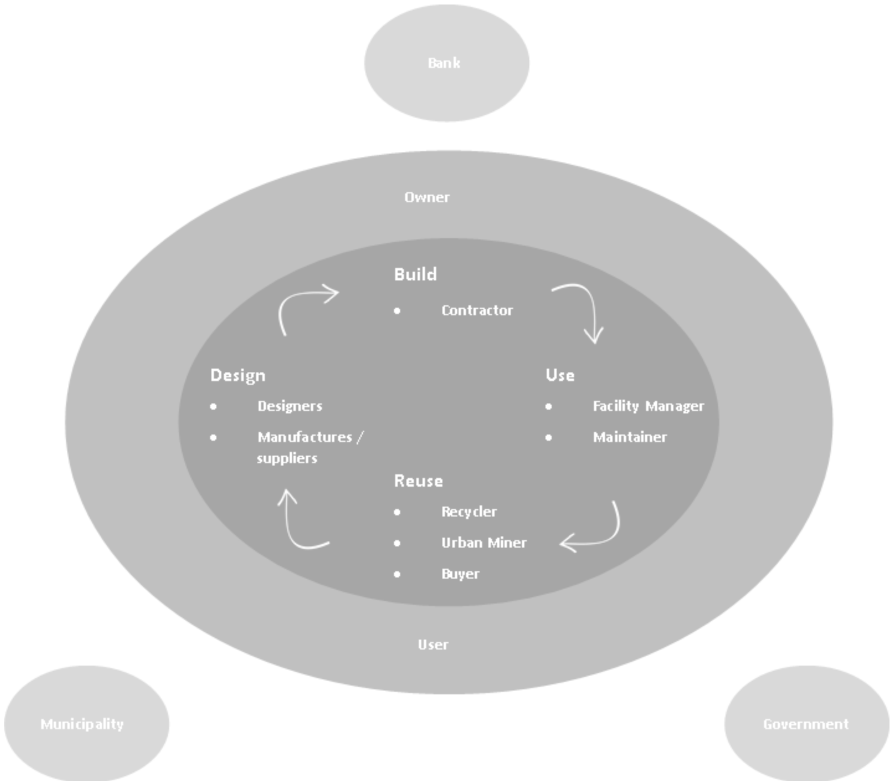


Figure 13: Actors building process (own illustration)

2.4.4 Challenges for moving towards a circular economy

Ritzén & Ölundh Sandström (2017) conducted a research towards the challenges that influence the implementation of a circular economy. There are many challenges identified and those are most often connected to each other. This clearly illustrates the complexity of a circular economy and what is required for a transition towards it. Figure 14 shows five different types of challenges. These are: financial, structural, operational, attitudinal, and technological. Kok, Wurpel, and Ten Wolde (2013) also mentioned different groups of challenges in their research. They mentioned the following groups: financial obstacles, insitutional obstacles, infrastructure, societal and value-related obstacles, and technological obstacles. In general these groups are in line with the groups that are mentioned by Ritzén & Ölundh Sandström (2017). For this research the structural challenges about the missing expanse of information are most relevant. The lack of an information and a material exchange system is blocking the exchange of materials between different actors after their first lifecycle (Winans, Kendall, & Deng, 2017; Kok, Wurpel, & Ten Wolde, 2013).

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

Figure 14: Challenges for moving towards a circular economy (Ritzén & Ölundh Sandström, 2017)

2.5 Material passports

Material passports are created for providing a solution for the missing information barrier, they are an active tool for value tracking and intended to be used to bring residual value to the market. To understand the circular value potential of products, systems, and materials, a reliable set of information is required as described within the previous paragraph. Actions in every stage of the lifecycle of a building, from production towards, use, maintenance, and demolish have impact on products and systems and their value recovery potential. A material passport will make this information available, relevant to all stages of the lifecycle of a building (Luscuere, 2017). Preventing the scarcity of raw materials is a main objective within a circular economy. However, very few information and material exchange instruments have been created over time. The instruments that are created are mainly operating on a small or local scale. To let these systems evolve from a local focus to a more wider scale requires trust, increases costs of the coordination, and most often reduces the quality of the information on which the system operates (Damen, 2012). In a circular economy it is inescapable to assemble high quality data on used products and materials, composition, supply chain, and properties. A systematic quality control of data and registration of it is important in order to keep it up-to-date. There is no system available on the market that facilitates this, BIM (Building Information Model) is often named as a possible solution (Geldermans, 2016). To let digital platforms work successfully certain information about materials and components need to be made available. Material passports will allow products to have traceability and contain information which can be translated to their residual value at the end of their life (Carra & Magdani, 2017; Debacker & Manshoven, 2016). In figure 15 the take, make, and dispose process without material passports is shown. In this figure is visible that in the current process (without passport) a data gap exists. Material passports are created as a solution for this problem, in the process (with passport) it is visible that the material passport fills in this data-gap. It is visible that the information inside the passport will facilitate the reuse loop of raw materials and products.

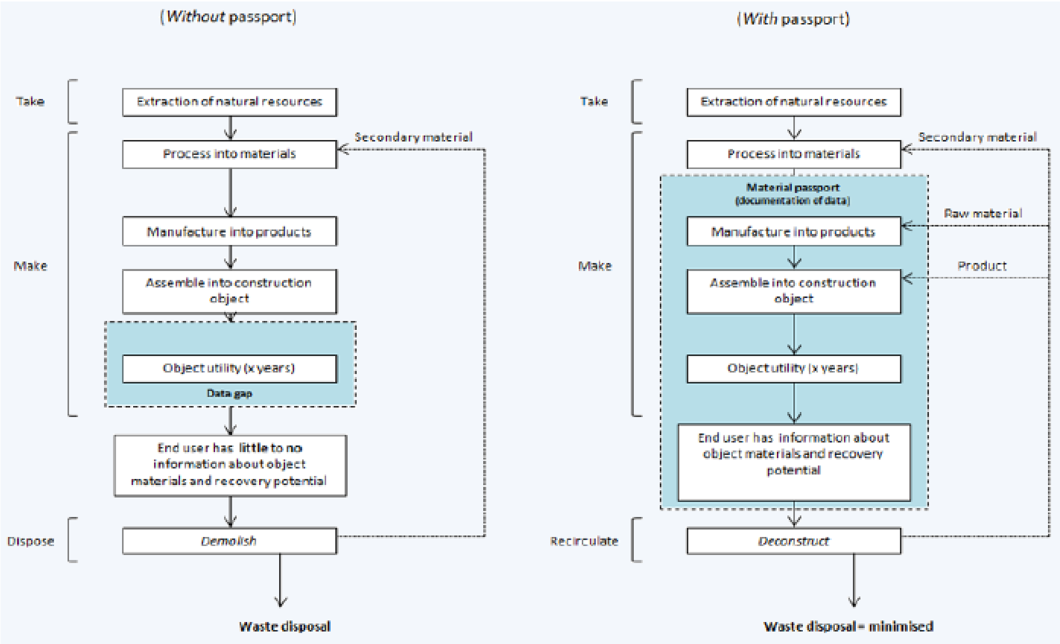


Figure 15: Information flow (Nagel & Korbee, 2017)

2.5.1 Definition material passport

A material passport records at material level what materials are used in a building or building components and how many are included. The resources that are used are recorded and can be passed on from supplier, contractor, owner, and finally to the demolisher or dismantler of a building (van Sante, 2017). Material passports can be described as follows:

> *"A material passport describes all the materials, components, and elements used in a building. It is a digital dataset that identifies which materials are included in the used parts, where they are located, how to disassemble them, who the owner is, and what the quality is when they become available for reuse. Thus, value of these materials can be allocated for reuse, resale and / or recycling. The material passport gives materials an identity and value"* (Bokeloh, Krayenhoff, Menkveld, Raes, & Schotsman, 2017, p. 15).

Derived from the research that was conducted by Damen (2012), a material passport needs to have certain characteristics. The provision of the information that is requested for the material passport should be done by every actor within the supply chain. This information should regularly be updated. The information that is stored in these passports need to be stored in such way that they are easy accessible but the confidentiality issues regarding the access of information need to be covered. The passport should also have an uniform format. The format of the material passport should be designed in such way that it still enables some kind of customization of the information that is stored within it. An example of the interface of a material passport is visible in figure 16. This example is from the LLMNT passport, this is the material passport from the CIRCL pavilion. As all current existing material passports have their own interpretation of what needs to be included it is chosen to use the LLMNT material passport as a definition of what a material passport is.

Luscuere (2017) stated that a material passport is more than just an ingredients list of a building. To strengthen this statement he gives the following five arguments. The value chainsof products are often complex and this is relevant in defining the composition of products in material passports. Products are often made from different parts or ingredients bought from different suppliers, which can in turn be made from certain ingredients bought from sub-suppliers and so forth. Also the materials that are relevant for a circular economy extends beyond the construction elements of a building. Elements can be placed in groups like climate systems, lightning systems, furniture, flooring, electronics, and biological materials. Many of these materials can flow through shorter cycles than the hull of a building. Materials inside a building a not useful when it is not clear where these material are located. Products and components can also be worth multiple times the value of their raw materials, these values depend on actual market conditions. An ingredients list based on basic materials turn the focus to commodity prices, this ignores the potential higher value of the products in which the materials are implemented. Finally, throughout the lifecycle of buildings from design to build to maintenance and adaption to new users, products used in buildings can frequently change. Tracking those changes is an important factor for having up-to-date information on the potential value of products, materials, and systems.

Figure 16: Interface LLMNT material passport (de Architekten Cie, ABN AMRO, 2017)

2.5.2 Content material passport

In the research 'A Resource Passport for a Circular Economy' Damen (2012) describes what the content needs to be for a material passport. In the material passport LLMNT from CIRCL (2017) many aspects of the resource passport from Damen (2012) were included. In figure 17 the contents of the material passport LLMNT are visible. This is an example of how a material passport can look. For this research this passport is used as definition of what the contents of a material passport are.

nr.	Potentie	Waarborging	Revisie	Specificaties
1	Circulaire potentie	Handleiding onderhoud	Logboek onderhoud	Prestaties
2	Demontage-vermogen	Handleiding beheer, aansluitingen	Logboek beheer, aansluitingen	Afmetingen
3	Datum van vrijkomen	Handleiding beheer, voorzieningen	Logboek beheer, voorzieningen	Gewicht
4	Financiële waarde	Handleiding beheer, afwerkingen	Logboek beheer, afwerkingen	Codering + naam
5		Handleiding montage	Logboek montage, As-built	Leverancier
6		Handleiding demontage	Logboek montage, gebreken	Certificaten
7			Logboek demon-tage, gebreken	Locatie
8				Oplevering
9				Eigenaar
10				Technische levensduur
11				Opbouw materiaal
12				Kringloop materiaal
13				Gevarenklasse materiaal

Figure 17: Content LLMNT material passport (de Architekten Cie, ABN AMRO, 2017)

Not all of the information is needed at every detail level in the material passport. The material passport LLMNT uses the same structure as is proposed by Durmisevic and Brouwer (2006). With this structure also the decomposition of a building as proposed in the 'Shearing layers' concept as proposed by Brand (1994) can be included in the decision making. These different levels are visible in figure 18. If the number is green then the information about the materials is included at that level of detail. With the orange numbers the information is the same on different levels and should be taken from the highest level. If the number is red the information is not included at that specific level (de Architekten Cie, ABN AMRO, 2017).

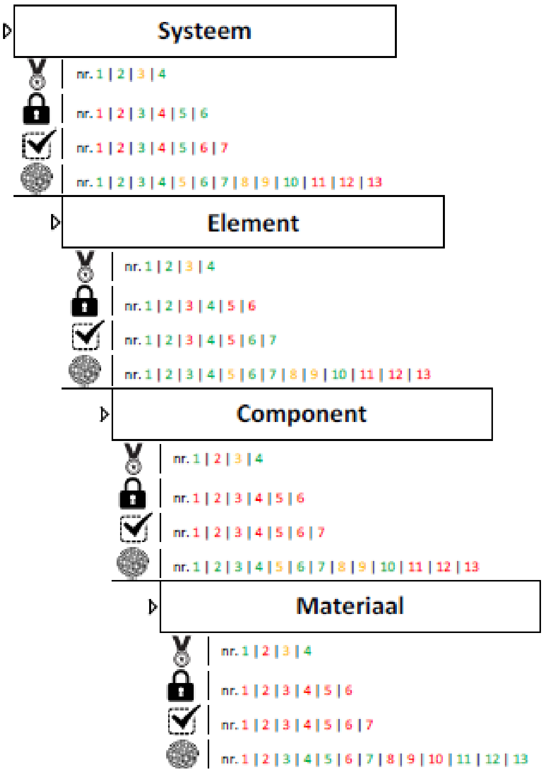


Figure 18: Levels of detail material passport (de Architekten Cie, ABN AMRO, 2017)

2.5.3 Actors material passport

In the report about the LLMNT material passport the stakeholders are divided into four different groups. These four groups are visible in figure 19 (de Architekten Cie, ABN AMRO, 2017). These stakeholders are directly working with the material passport and therefore important to include in this research. These groups correspondent with the different stages of the lifecycle of a building described in the researches of Debacker and Manshoven (2016) and Pomponi and Moncaster (2016).
The actors that give input to the material passport are the core actors that are also described in figure 13. All these actors have different inputs and outputs in the system. Those inputs and outputs are

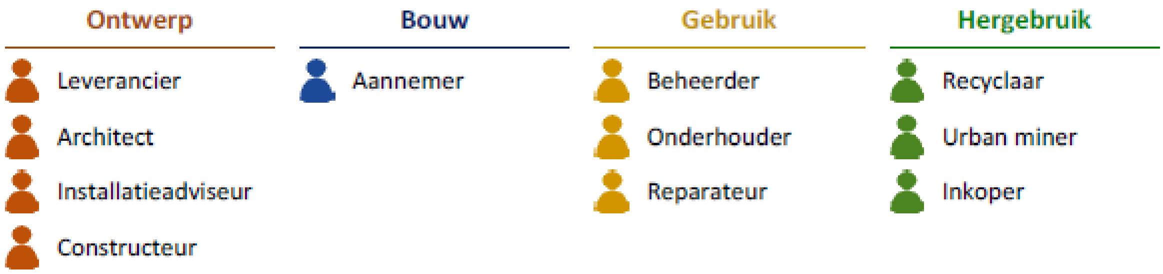


Figure 19: Stakeholders material passport (de Architekten Cie, ABN AMRO, 2017)

described in appendix ii.

2.5.4 Opportunities material passports

Debacker and Manshoven (2016) analysed in their research different opportunities that could stimulate the use of material passports. They stated that the use of material passports helps in lowering the environmental impact of the built environment. They support the reuse of materials which will have a positive effect on actual re-using them. Material passports will also be used to exchange valuable information within the value network. The use of an information platform should allow subcontractors to collaborate and communicate with each other. It will allow actors in the demolition phase to get a better view on the building elements and materials that are usable for reuse or remanufacturing. Availability on the information about materials, maintenance, and status in a digital passport of a building opens opportunities for product suppliers to access the information if they want to buy back their products, reuse the products, or during the maintenance cycle. The use of material passports will also open the door for new business models within a circular economy.

2.5.5 Barriers material passports

Debacker and Manshoven (2016) also analysed different barriers that could prevent the implementation of material passports. The fragmented European Union municipality policies result in a lack of integration. For example, the current urban regulations and building permits are based on a linear instead of a circular vision. This vision may impede the changes and transformation possibilities created by material passports. Besides this there is also a lack of robust and standardised data over the entire value chain of a building. Also the intellectual property of material and product related data is seen as a barrier. Balancing intellectual property on material and product related data with open source data remains a challenge but is necessary for the success of material passports. Also the linear construction models need to be changed into circular ones. At this moment there is a lack of certification and quality assurance for reclaimed materials and products.

2.5.6 Information exchange material passports

As the importance of the material passport now has been discussed, there can be discussed how the information inside material passports need to be exchanged. To facilitate the sharing of qualitative information it is important to understand the factors that influence information sharing in order to develop a strategy. Research shows that the following factors have a great impact the willingness to share information; a shared vision within the supply chain, trust within the supply chain, and supplier uncertainty (Li & Lin, 2006). Damen (2012) stated that an information exchange system for material passports need to have the following five format elements in order to succeed; provision, storage, access, quality, and presentation of the information.

Provision of the information

To get a good information exchange within the supply chain, someone that takes responsibility for the coordination is necessary. However, there is no single authority that has control over the whole supply chain. The cooperation in a supply chain is through negotiation instead of through central management and control (Jain & Benyoucef, 2008). Cooper, Ellram, Gardner, and Hanks (1997) stated that cooperation is necessary to provide the information and this is not limited to the involvement of solely top and operational management levels. The provision of the requested information for the material passport requires the cooperation of many different departments within a company. The information should be transferred directly from one element to the next element downstream through the supply chain, or it should be transferred to a third party that will put the information into the information system, or it should be directly transferred to an information system that manages the whole supply chain (Lee & Wang, 1998).

Storage of the information

Data volume continues to grow tremendously because the service and manufacturing sectors are adopting new technologies like the use of sensors (Zhong, Newman, Huang, & Lan, 2016). Within a material passport each company is responsible for its own data, therefore Bechini, Cimino, Marcelloni, and Tomasi (2008) suggest to store the data local in for example in-house-servers and transfer the data only when it is requested by means of a pull function to a centralized database of for example a thrusted third party.

Access to the information

From a conducted survey addressing the information sharing practices in supply chains, it can be concluded that confidentiality issues regarding information sharing is one of the major hurdles for supply chain wide information sharing, this applies primarily for competitive environments (Lee &

Wang, 2000). Confidentiality of the information that is stored means that the information that is accessed is secure from unauthorized disclosure. Companies can be restrained to share data due to possible information leakage resulting in strategic actions by competitors (Smith, Watson, Baker, & Pokorski II, 2007). Sharing information across the supply chain can result in that confidential information is spread which, for example, could decrease competiveness in further negotiations. Companies may also fear leaking other companies confidential information and then being regarded as a less trustworthy partner. Especially when information is shared with a multitude of companies, it is dificult to control exactly what information is shared with whom (Kembro, Näslund, & Olhager , 2017). Bechini, Cimono, Marcelloni, and Tomasi (2008) suggest in order to guarantee the confidentiality of the data, it can be stored on privatly owned in-house-servers and others are only provided with the tracability of the information. In this structure a data-trustee is necessarry. A data-trustee is a trusted third party that is trusted with the ownership of the data. The date-trustee acts like an escrow agent, it holds the actors data untill a legitimate moment arises where the data needs to become visible. Bechini, Cimono, Marcelloni, and Tomasi (2008) also suggest to use multiple data-trustees, in this way can companies choose their own data-trustee.

Quality of the information

The information quality is an important element in the supply chain management literature and refers to the accuracy, timelines, adequacy, and credibility of the information that is exchanged. The information sharing and quality improves when there is a shared vision and trust in the supply chain. The quality of the information is also influenced by supplier uncertainty and the length of the supply chain. When a supply chain is longer the chance for delays or distortions in the data will increase. Partnerships are proposed as a possible solution (Li & Lin, 2006). Jain and Benyoucef (2008) described that businesses are becoming more web-based which will result in improved quality of the information because information is automatically updated with for example sensors.

Presentation of the information

Lambert (2001) states that unification of the method of description is indispensable since there is a need to understand the information at every stage of the supply chain. Unification enables decision making through the whole supply chain and will allow the different stakeholders to quickly evaluate the available information. Because there is no centralized planner within the supply chain and the decision making occurs in a decentralized way, it is important that the information is presented in a unified but decentralized model (Sahin & Robinson, 2002).

Damen (2012) stated in her research that the creation of a shared vision in the supply chain is what the development of the material passport is all about. The barriers trust and supplier uncertainty will be addressed by the different format elements that are described in this paragraph. The provision of the requested information that is stored within the material passport should be done cooperatively within the whole supply chain. All the actors are self-responsible for the information that is stored in the material passport. This information need to be updated regularly to ensure the quality, the definition of regularly depends on the type of information that is stored. The information that is stored within the material passport should be uniform within for whole supply chain.

2.6 Conclusion

It can be concluded that a circular economy has an answer to the limits of the linear economy. A circular economy and all the related principles can be summarized as an economy that is restorative by intention and that relies on renewable energy. The concept aims to minimize, track, and eliminate the use of toxic materials and minimize waste through careful design. This is accomplished by the use of thinking in systems and redefining the supply chain towards a closed loop. The end of life scenario of a product is not only limited to become nutrients for new products. It is enhanced with options for materials that are not suitable to give back to nature. For these products the closed loops exist out of reusing, refurbishment, repairing, and recycling. It is expected that this end of life treatment has an economic value to the owners of the products when the economic value of used products increases. For this reason it is important to gain insight into material flows, the design of a product, and the end of life possibilities. This produces a vast amount of data, which then must be extracted in an effective and efficient way in order to link the material cycles to each other.

Material passports are created to facilitate the information gap that currently exists within a circular economy. They are an active tool for value tracking and intended to be used to bring residual value to the market. Actions in every stage in the lifecycle of a building, from production towards, use, maintenance, and demolish have impact on products and systems and their value recovery potential. Another aspect of buildings is that they can change a lot during their lifecycle because of their long lifetimes and different users. Tracking those changes is an important factor for having up-to-date information on the potential value of products, materials, and systems. The provision of the requested information that is stored within the material passport should be done cooperatively within the whole supply chain The information should be updated regularly to ensure its quality. The definition of regularly depends on the type of information that is stored. There is also a lack of robust and standardised data over the entire value chain of a building. Also the intellectual property of material and product related data is seen as a barrier. Balancing intellectual property on materials and products with open source data remains a challenge but is necessary for the success of material passports. As last is there at this moment a lack of certification and quality assurance for reclaimed materials and products. Also the linear construction models need to be changed into circular ones to facilitate all these new information flows.

3. Literature review: Blockchain technology

This section aims to provide a framework on blockchain technology in order to understand the working mechanism, key aspects, and the main applications. It aims to provide a technological framework that will be used in the following chapters. To structure this chapter the structure as described by Hileman and Rauchs (2017) is used, visible in figure 20. They conducted a global benchmark study to provide an overview of where this technology stands now. This structure is therefore based on the different initiatives that are created upon now. Hileman and Rauchs (2017) uses three layers to describe the blockchain architecture namely:

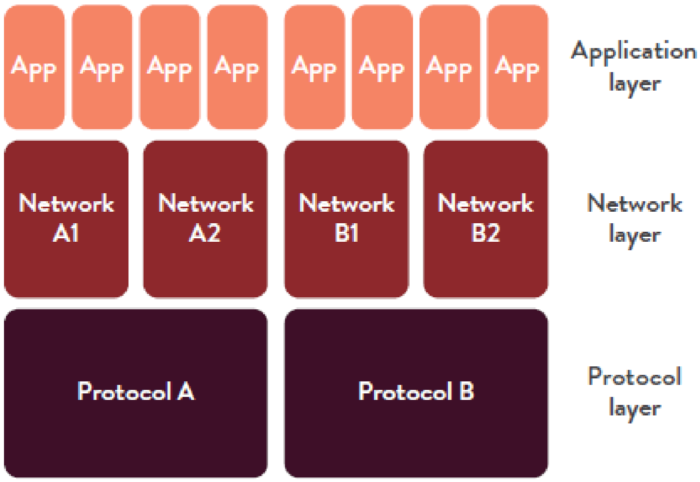


Figure 20: Blockchain technology system layers (Hileman & Rauchs, 2017)

- **Protocol layer:** The protocol layer includes the core software that creates the backbone of the blockchain. This layer is the infrastructure (chain of blocks) of which the networks and applications are built. The protocol itself does not deliver any value without the network layer;
- **Network layer:** The network layer consist of the actual peer-to-peer network that brings the blockchain to life by connecting the participants. When people talk about a specific blockchain technology, they usually mean a particular network. The network can be industry specific, use case specific and, enterprise specific;
- **Application layer:** The application layer constitutes primary the use interface for the blockchain network. It is built on top of the network and provides products and services.

3.1 Definition blockchain

Before further explanation on the phenomena blockchain, it is good to provide a short overview on the first blockchain application named Bitcoin. In a whitepaper Satoshi Nakamoto (2008) proposed Bitcoin as the first electronic payment system that is based on a decentralized peer-to-peer network without the need for a thrusted third party. The core technology behind this protocol is called the Bitcoin blockchain. This technology is widely acknowledged as a major breakthrough in fault tolerant distributed computing after decades of research in this area. The Bitcoin blockchain can be defined as a database that contains all the transactions ever executed in the Bitcoin network. It consists of a permanent digital distributed ledger that is resistant to tampering and carried out collectively by all the nodes in the whole system (Atzori, 2015). The Bitcoin blockchain aims to revolutionize the worldwide payment system. It consists of a virtual currency that is transacted among its users, also defined as the nodes that participate on the Bitcoin blockchain network. Bitcoin was the first virtual currency that solved the issue of ‘double spending’. The risk of double spending is about making a digital transaction while keeping the original copy of the transacted asset. The Bitcoin blockchain solved this risk with its distributed ledger structure, which substitutes the thrusted third party in its role of recording every transaction that is carried out (Francisconi, 2017).

The terms Bitcoin and blockchain are often used interchangeably. Brenig, Schwarz, and Rückeshäuer (2016) describe that Bitcoin is just one of the several possible applications on a blockchain network. In other words the blockchain is just the technical backbone on which Bitcoin is build. Since the aim of this research is to analyse blockchain technology, it is not relevant to describe the application of

Bitcoin. However, it is relevant to describe the aspects of the Bitcoin blockchain (public permissionless blockchain) as a platform to illustrate the possibilities of this new technology.

The technology of blockchain can be decomposed in some core aspects. In this paragraph the protocol / network layer will be explained by the different characteristics. The different aspects of blockchain are structured on the basis of different studies. In table 5 the different aspect of different studies are compared.

Table 5:Overview core characteristics blockchain technology

<table>
<tr><th>Hileman and Rauchs (2017)</th><th>Morabito (2017)</th><th>Tapscott and Tapscott (2016)</th><th>Tasca, Thanabalasingham, and Tessone (2017)</th><th>Corresponding characteristics</th></tr>
<tr><td rowspan="2">P2P network</td><td rowspan="2">Decentralisation</td><td>Distributed power</td><td rowspan="2">Decentralisation and consent</td><td rowspan="2">Distributed</td></tr>
<tr><td>Inclusion</td></tr>
<tr><td>Ledger</td><td>Provenance</td><td>Rights to preserved</td><td>Transparency</td><td>Transparency</td></tr>
<tr><td>Consensus mechanism</td><td rowspan="2">Resilience and irreversibility</td><td rowspan="2">Network Integrity</td><td rowspan="2">Immutability</td><td rowspan="2">Immutability</td></tr>
<tr><td>Validity rules</td></tr>
<tr><td rowspan="2">Cryptography</td><td rowspan="2">Trust</td><td>Security</td><td rowspan="2">Security</td><td rowspan="2">Security</td></tr>
<tr><td>Privacy</td></tr>
</table>

3.2 Protocol / Network Layer

The aim of this section is to give a clear understanding of the blockchain platform. Following the characterization of Hileman and Rauchs (2017), the Protocol and Network layer can be identified as the protocol of the technology, which is the foundational base for the other layer. This is also endorsed by Mougayar (2016). Crosby, Nachiappan, Pattanayak, Verma, & Kalyanaraman (2016) described a blockchain as follow:

> *"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 public ledger is verified by consensus of a majority of the participants in the system."* (Crosby, Nachiappan, Pattanayak, Verma, & Kalyanaraman, 2016, p. 7).

The following paragraphs will provide a technical description of blockchain technology. This description aims to provide an overview on the technical aspects behind current and future market applications. First the network structure of a blockchain is described. After this the ledger structure of a blockchain is explained. This is followed up with the blockchain transaction mechanism. The fourth paragraph is about the consensus mechanism blockchain. Finally, the different types of blockchain are presented. This structure is aligned with the different characteristics from table 4.

3.2.1 Network architecture (Distributed)

The network of a blockchain can be characterized as a distributed network. This is also one of the key features of this technology (Swan, 2015). The transfer of the ownership of value is done in a transparent way and without the help from a third party (Morabito, 2017). The part that makes blockchain a transformative innovation is that every node on the network has a copy of the whole ledger with all historical transactions. This eliminates the need for a central database and ensures that a single user is unable to manipulate the data that is written on the blockchain (Spielman, 2016). The system distributes power across a peer-to-peer network with no single point of control. No single party can shut the system down. If over half the network attempts to overwhelm the whole, everyone will see what is happening (Tapscott & Tapscott, 2016). Centralized data storage and management systems are susceptible to hacking, intrusion, and breaches. The blockchain distributed network makes it more difficult for the network to experience attacks (Xu, 2016). Despite every node holds a copy of the whole ledger, only the nodes that hold the key can access the information. The blocks on the blockchain can be seen as containers where data is stored. These containers are sealed and their content can only be seen by those who hold the permission (Morabito, 2017). In figure 21 the difference between a centralized, decentralized, and distributed network is visible.

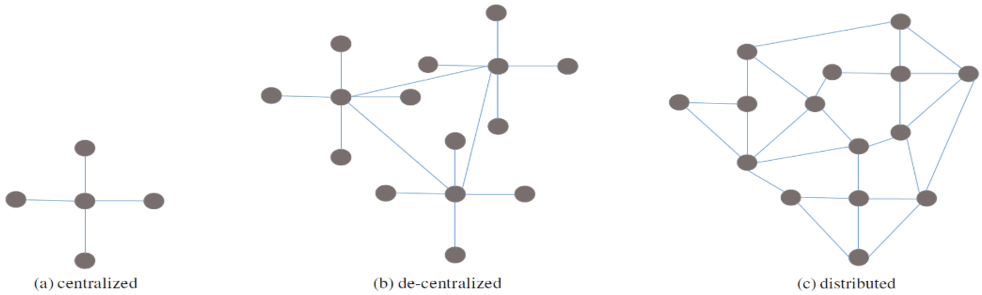


Figure 21: Comparison centralized, decentralized, and distributed (Morabito, 2017)

3.2.2 Ledger architecture (Transparency)

A blockchain can be defined as a database of records that consists of all the transactions that has been carried out and shared among the participants within the network (Morabito, 2017). The records inside a blockchain are auditable by a predefined set of participants. This set of participants can be more or less open, this depends on the type of blockchain that is used. (Tasca, Thanabalasingham, & Tessone, 2017). Figure 22 gives a visualization of a chain of blocks. Each block is composed of block header and body. The block header includes the information of the previous and following block header hash and the timestamp. On the other hand the block body contains the number of transactions and the collection of transactions which have inputs and outputs (Zheng, Xie, & Dai, 2016).

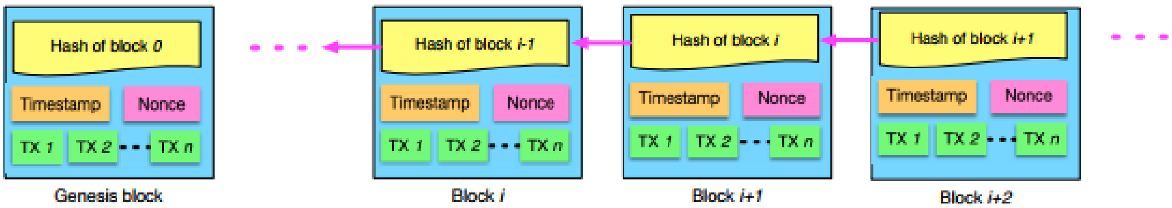


Figure 22: Visualisation blocks (Zheng, Xie, & Dai, 2016)

Each node in the blockchain network holds a set of keys (private and public). The private key is used to encrypt the transactions before sending them, this is visible in figure 22. The receiver can use the public key of the receiver to decrypt the transaction. Before the transaction is recorded on the blockchain the transaction needs to undergo two different phases: the singing and verification phase, this is also visualized in figure 23. The signing phase consists of the encryption of the data with the private key. The verification phase consists of the solution of a computational problem which ensures that the same transaction is not happening twice, for the decryption the public key of the sender is used (Morabito, 2017). The decentralised consensus on transactions is governing the update of the ledger by transferring the responsibilities to the local nodes which independently verify the transaction. There is no central authority required to approve transactions and set the rules (Tasca, Thanabalasingham, & Tessone, 2017).

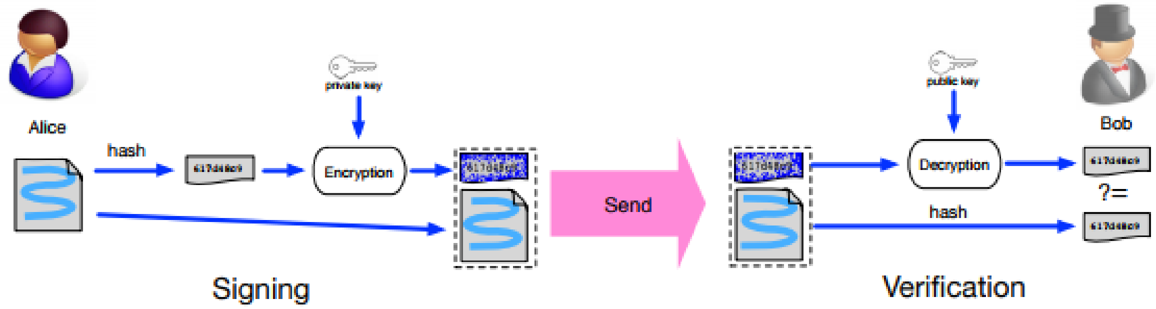


Figure 23: Digital signature used in blockchain (Zheng, Xie, & Dai, 2016)

3.2.2.1 Blockchain transaction mechanism

The transaction mechanism of a blockchain network can be described in five phases (Morabito, 2017; Frøystad & Holm, 2015). Figure 24 shows the five phases.

- **Transaction definition:** The sender generates a transaction and sends this towards the network. This transaction includes the receivers public address, the value of the transaction, and a cryptographic digital signature that proves the authenticity of the transaction.
- **Transaction authentication:** After the transaction is send to the network, the transaction is received by the nodes which will authenticate the validity of the message by decrypting the digital signature. The authenticated transaction is waiting in a pool of pending transactions until a block is created.
- **Block creation:** The pending transactions are put together in an updated version of the ledger, called a block by one of the nodes inside the network. At a specific time interval the node will broadcast the block to the network for validation.
- **Block validation:** The validator nodes of the network receive the proposed block and validate this trough an iterative process which requires the consensus of the majority of the network. The different blockchain networks uses different validation techniques. The Bitcoin Blockchain uses a technique that is called “proof-of-Work”, and Ethereum uses the “Proof-of-stake” concept. The different techniques have different pros and cons, the common dominator is that they ensure that every transaction is valid, this makes fraudulent transactions almost impossible (Zheng, Xie, & Dai, 2016). The different techniques are described in paragraph 3.2.4.
- **Block chaining:** When all the transactions are validated the new block is chained into the blockchain, the new current state of the ledger is broadcasted to the network. On this verified version of the blockchain the new blocks will be recorded.

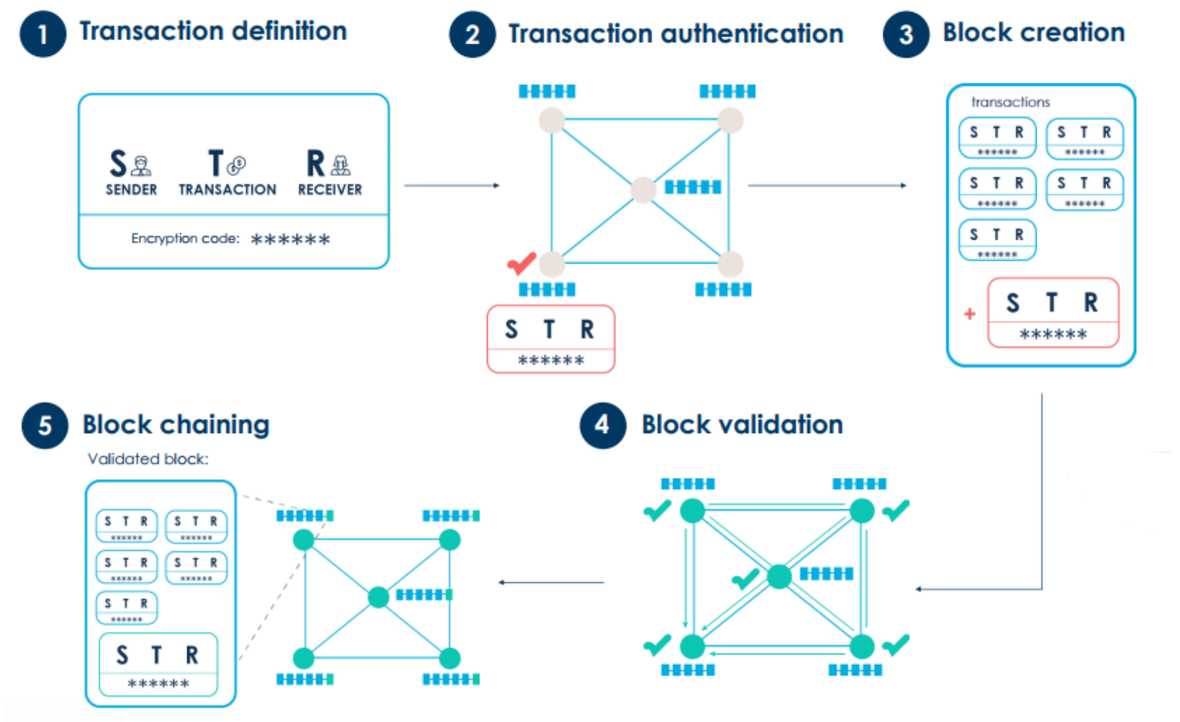


Figure 24: Overview blockchain transaction (Frøystad & Holm, 2015)

3.2.3 Cryptography (Security)

Safety measures are embedded in the network with no single point of failure, and they provide not only confidentiality but also authenticity to all activities. Anyone who wants to participate must use cryptography, opting out is not an option. And the consequences of reckless behaviour are isolated out to the person who behaved recklessly (Tapscott & Tapscott, 2016). To verify the validity of the different blocks of the blockchain, heavy cryptography is used. By the variety of cryptographic techniques including the cryptographic one way hash functions, Merkle trees, and the public key infrastructure makes that the security is guaranteed (Hileman & Rauchs, 2017). Inside the blockchain hash pointers are used to connect the blocks. Each block has data as well as pointers towards the previous blocks in the list. So each block does not only tell where the value of the previous block is but also contains a digest value that allows to verify that the value has not changed. Another important aspect of the blockchain system is the ownership and the ability to transfer the units of ownership to other users.

To reduce the space that is needed for the data on the blockchain and to make sure that it is possible to show it on the smallest device a merkle tree is used. A merkle tree is also named as a binary hash tree, it is a data structure that is used for efficiently summarizing and verifying the integrity of large data sets. Simply said, a merkle trees are binary trees that contains cryptographic hashes. Merkle trees are used to summarize all the transactions within a block. This produces a digital fingerprint of the entire set of transactions that are stored within a block. This provides a very efficient process to verify whether a transaction is included in a block (Dijkstra, 2017).

Blockchain technology relies on the usage of asymmetric cryptography to sign the digital signatures and encrypt data through the use of private and public key pairs (Kuan Hon, Palfreyman, & Tegart, 2016; Spielman, 2016). The public key creates a public shareable address for the user by creating a unique string of numbers and letters. The private key is used on the other hand to sign the public key and to create an unique digital signature. This signature, when submitted, is used to create a transaction on the blockchain network (Spielman, 2016). The private key which will allow a given entity to transact with the ownership of assets allocated on the blockchain, these assets are stored in what is called a wallet. In a given wallet multiple keys can be stored (Kuan Hon, Palfreyman, & Tegart, 2016).

3.2.4 Consensus mechanism (Immutability)

The blockchain transparency aspect makes it also a robust network, since it is designed as a distributed network of nodes where in each of these nodes a copy of the entire chain is stored. When a transaction is verified and approved the by the participating nodes, it is highly impossible to change or alter the transaction data (Morabito, 2017). The core difference between a distributed ledger and a traditional database is the difference in how the dataset evolves over time. The blockchain allows multiple participants to submit new inputs to the distributed ledger. Consensus is used to determine over time which state of the distributed ledger is considered as valid. This is in contrast to a traditional database where the multiple participants submit new inputs and one counterparty is relied on providing the valid state of the database. The consensus protocols are the mechanisms by which all users within a distributed ledger agree on the validity of the underlying data (Kuan Hon, Palfreyman, & Tegart, 2016). A blockchain is a shared, tamper-proof, replicated ledger where records are irreversible and cannot be forged thanks to one-way cryptographic hash functions and the consensus mechanism. It becomes very difficult for an individual or any group of individuals to tamper with the ledger (Tasca, Thanabalasingham, & Tessone, 2017). Therefore is blockchain often linked to immutability. The term immutable means that something that is stored cannot be changed over time or the values remain the same over a specific period of time. This means in context to the blockchain that stored data within blocks cannot be changed by anyone, even not an administrator. The process of a single rewrite is almost impossible and would require a consensus from the majority (51%) of all the members of the network. Any attempt to modify the contents of any block or transaction would require a recalculation of the block's key hashes. A recalculation of the hashes would also lead to a break in the entire chain because the blocks are linked with their key hashes (Morabito, 2017).

A blockchain platform is a system that utilizes cryptography to secure transactions in a verifiable distributed ledger of records. This new concept redefines the intermediary role (thrusted third party) as a guarantee of the systems validity. The trust inside the system does not rely anymore on the intermediary role but on the consensus mechanism. The consensus mechanism is the process in which the majority of the network validators come to agreement on the state of the ledger (Swan, 2015). The consensus algorithm of a blockchain allows users to securely update states using pre-defined state transition rules where the rights to state the transition are distributed to all the nodes inside the blockchain network. Consensus provides a protocol by which the new blocks are approved and added to the ledger (Morabito, 2017). Morabito (2017) describes that there are three things needed for the concept of consensus.

- Common acceptance laws, rules, transitions, and states in the blockchain;
- Common acceptance of nodes, methods, and stakeholders that apple these consensus laws and rules;
- Sense of identity such that members feel that all member are equal under the different consensus laws and rules.

The main types of consensus protocols can be described as follows:

- **Proof of Work:** With the 'Proof of Work' protocol miners create a proposed block with transactions and create a hash of the block headers. The miners match this hash to the intending target or the last block of the desired chain. If the hash does not match, it will repeat the calculation but with an adjusted cryptographic number called a "Nonce". Nonces are use inside the cryptographic function to change the input until a match is found. A Nonce can only be used once and is usually updated by simply incrementing it by one. The block can be added to the chain when a match is found (Morabito, 2017);

- **Proof of Stake:** With the ‘Proof of Stake’ protocol the stakeholders with the highest incentives in the system are identified and only these stakeholders participate in mining. An active participation on the blockchain network gives participants the rights to generate new blocks for the chain. Blocks are generated in the same way as in the ‘Proof of Work’ protocol except hashing is done in a limited search space instead of the unlimited search space of the ‘Proof of Work’ protocol (Morabito, 2017);
- **Practical Byzantine Fault Tolerance:** The ‘Practical Byzantine Fault Tolerance’ can be attributed to a form of distributed consensus and is peculiar to distributed networks. In a blockchain network each node will broadcast a hashed key. Transmissions flowing through each node and are signed and verified by the nodes in relation to the format and content. After a certain amount of responses a consensus is achieved and the transmission is validated. This protocol eliminates the hashing protocol and can manage a large number of transactions (Morabito, 2017).

3.2.5 Different types of blockchain

The original blockchain that was developed for Bitcoin by Satoshi Nakamoto (2008), was an open permissionless blockchain. However, this type of structure is not applicable to all blockchain applications that are currently developed. Despite the scope within this research is focussed on the public permissionless blockchain it is important to briefly focus on the other types of blockchain that are developed in order to give a good reflection upon this research. In order to identify these new permissioned blockchains from the public permissionless blockchains the industry started to use terms like private, closed, and permissioned. With these terms they refer to the restricted access of a specific set of participants. In practice these terms are used interchangeably. To create more clarity, blockchains can be further segmented by distinguish different permission models. Those permission models refer to the different types of permission that is granted to the participants of the blockchain network (Hileman & Rauchs, 2017; Francisconi, 2017).

Hileman and Rauchs (2017) distinguish three different types of permission that can be set when configuring a blockchain network:

- Read capability (who can access the ledger and see the transaction);
- Write capability (who can generate transactions and send them to the network);
- Commit capability (who can update the state of the ledger).

In figure 25 the four different main types of blockchain networks are segmented on their permission model. In this model public / private refers to the read capability and permissionless / permissioned refers to the write and commit capability.

Blockchain types			Read	Write	Commit	Example
	Open	*Public permissionless*	Open to anyone	Anyone	Anyone*	Bitcoin, Ethereum
	Open	*Public permissioned*	Open to anyone	Authorised participants	All or subset of authorised participants	Sovrin
	Closed	*Consortium*	Restricted to an authorised set of participants	Authorised participants	All or subset of authorised participants	Multiple banks operating a shared ledger
	Closed	*Private permissioned ('enterprise')*	Fully private or restricted to a limited set of authorised nodes	Network operator only	Network operator only	Internal bank ledger shared between parent company and subsidiaries

Figure 25: Main types of blockchains segmented by permission model (Hileman & Rauchs, 2017)

The key differences between the open and closed blockchains is the difference in security and threat model (Hileman & Rauchs, 2017; Francisconi, 2017). Public blockchains are operating in a hostile environment with unknown participants. Here is a rewarding system (rewarding miners) applied to incentivise participants to behave honestly and keep the network censorship resistant. In contrast private permissioned blockchains operate inside an environment where participants are already known and vetted. This removes the need for a native token to incentivise good behaviour (Hileman & Rauchs, 2017).

3.3 Application layer

This paragraph describes the application layer that is built on top of the Protocol / Network layer as described by Hileman and Rauchs (2017). These applications are linked to the core infrastructure of blockchain. The aim of this paragraph is to provide an overview on the possible blockchain applications. Therefore, the application on the market will not be described, but the concepts of Smart Contracts and Internet of Things will be described.

3.3.1 Smart contracts

The concept of smart contracts was first discussed in Nick Szabo's paper back in 1997. In that paper he proposed smart contracts as a means to embed a contractual clause into digital assets. Smart contracts are computer protocols that facilitate or enforce contractual clauses based on events such as time or user actions. Smart contracts require transparency and trust between the contractual parties for digital assets, the emergence of blockchain reignited the discussion of smart contracts as an application (Schillebeeckx, Soriano, & Teo, 2016).

> *"A smart contract is a computer program that both expresses the contents of a contractual agreement and operates the implementation of that content, on the basis of triggers provided by the users or extracted from the environment"* (Idelberger, Governatori, Riveret, & Sartor, 2016, p. 168).

A contract in the traditional sense is an agreement between two or more parties that fulfils an action in exchange for something else. Each party must trust the other parties to fulfil its side of the contracted obligation. Smart contracts feature the same kind of agreement, but they remove the need for one type of trust between the parties. This is because a smart contract is defined and executed by the code, automatically without discretion (Swan, 2015).

Ethereum is currently the world largest smart contracting platform. They state that a smart contract enables the exchange of money, property, shares, or anything of value in a transparent and conflict free way without the need to for a trusted third party to clear the transaction. As a result this technology eliminates the counterparty's risk and therefore dramatically diminishes transaction costs by getting rid of the middleman (Ethereum, 2017).

3.3.2 Internet of Things

The Internet of Things (IoT) is currently experiencing growth in research and industry, but the technology still suffers from privacy and security vulnerabilities. These issues can be solved with a scalable, trust less, peer-to-peer technology that is able to operate in a transparent and secure environment. Therefore, blockchain technology shows potential to become the technological platform that will enable IoT implementation (Dorri, Kanhere, & Jurdak, 2017). Dorri, Kanhere, and Jurdak (2017) describe that there are three blockchain characteristics that make this technology a potential for interconnected IoT, namely; decentralization, anonymity, and security. The decentralized aspect of blockchain technology ensures scalability and robustness by avoiding the issue of a single point of failure within the network. The technologies anonymity and security ensures the device's user privacy and security against untrusted parties who can access sensitive personal information.

3.4 Opportunities material passports

A vast amount of companies is getting a better understanding of blockchain technology and therefore new ideas and applications are emerging. In the financial industry blockchain is already a major topic on the agenda, ABN AMRO is contributing therefore in different consortiums like the Dutch Blockchain Coalition, R3, and Hyperledger. At this moment blockchain is also making its way into the construction sector. By analysing the different opportunities that are mentioned inside the literature, the following three opportunities are interesting for the implementation of blockchain technology for material passports:

- Digital records of real estate assets;
- Traceability of materials;
- Determining data source.

3.4.1 Digital records of real estate assets

A blockchain can be used for the registration of any form of asset (Swan, 2015). In real estate the whole lifecycle of buildings can de digitalized and transferred on a blockchain. Imagine a system where every property has its own digital passport with all the specific information about this asset.

The next step in digitalizing the real estate assets on a blockchain is the pilot project "Torch" from ABN AMRO. Although Torch is operating on a permissioned blockchain, this blockchain pilot gives insight in all the available information for the different stakeholders. Through the "Torch" platform, data is validated and exchanged between different parties such as real estate investors, appraisers, banks, and the Dutch central bank. Blockchain technology automatically guarantees the integrity of this data, allowing authorized parties direct access to accurate and up-to-date information. This means, for example, that it allows the Dutch central bank to perform audits at any time without prior reporting to an extensive reporting process (Zaat, 2017). Despite the challenges and the early phases of pilot projects, they show the potential that blockchain can enable property, to have a corresponding digital address that contains the occupancy, finance, legal, building performance, and physical assets and maintains all historical transactions. In addition, this information will be immediately available for all parties (Ray, 2015).

3.4.2 Traceability of materials

In addition to the digital passport that is described within the previous opportunity, materials can also be implemented in these passports, which will create a material passport within the digital passport. There are billions of products manufactured every day, through complex supply chains. However, there is currently very little information available of how, when, and where these products were originated, manufactured, and used throughout their lifecycle (Abeyratne & Monfared, 2016).

Abeyratne and Monfared (2016) propose a distributed system that uses blockchain technology to collect, store, and manage the information about products throughout their lifecycle. Such distributed network of information potentially creates a secure, shared record of transactions, for each individual product combined with the specific information of each product. Blockchain technology can improve the transparency and traceability within the supply chain through the use of an immutable record of data, distributed storage, and controlled user access. A shared, consensus based, and immutable ledger helps track the origin and the transformation of the product through the supply chain. The blockchain can create a forma registry enabling the identification and tracking of possession of a product throughout the supply chain (Kshetri, 2017; Pilkington, 2016). Sensors within the internet of things can capture real time data about products and their environmental characteristics as well as their location and timestamps of their journey through the supply chain and the lifecycle of a building. The lack of a digital footprint of a product may no longer be a problem. Furthermore, blockchain technology promise to offer highly secure and immutable access to supply chain data. Blockchain technology is decentralized so that the provenance on products can be evaluated, even when no party can claim the ownership over the whole supply chain (Kim & Laskowski, 2016).

Also regarding the sustainability standards and certifications of materials can blockchain technology offer an added value. Those standards and certificates like Fairtrade or FSC Wood support the decision making of consumer by providing them with a better understanding of the origin of the product. However the end product is only a printed logo of the certification on the product and consumers are encouraged to accept this information without being able to verify it. Verifying claims is a costly process that requires extensive auditing (Abeyratne & Monfared, 2016). Furthermore, the extension of certification schemes within regions with levels of high corruption can further endanger the credibility of such standards (Provenance, 2015). However, Also in regions with no corruption, the credibility of such standards cannot always be granted. One recent example of the abuse of trust in reputable companies is the Volkswagen emissions scandal in 2015 (Cremer & Taylor, 2016). The problems arising from the abuse of trust such as fraud have a significant negative impact on business. The global financial cost of fraud is estimated to have been more than $4 trillion alone in 2016 (Hileman & Rauchs, 2017).

3.4.3 Determining data source

An actual problem within our age of big data is determining the source of information (Kim & Laskowski, 2016). This will also be a challenge within material passports to determine the validity of the data that is stored. Blockchain can have a big impact on information sharing systems. Morabito (2017) expects that blockchain technology will revolutionize the nature of information sharing across different actors. A key benefit of blockchain technology for supply chain networks is that it establishes a shared, secure record of information. It will create a 'shared version of events' across the networks for supply chain transactions, processes, and partners. When a block is created on the blockchain with trustworthy data, and each additional transaction is validated by the network consensus, then in theory the current state of the ledger can be trusted. This will establish a high level of data integrity, thereby making data trusted, available, secure, and compliant for everyone (IBM, 2017).
Also within the construction industry where BIM is used to share a lot of information, blockchain can have a big impact. With blockchain technology BIM models can be improved on the topics of confidentiality, provenance tracking, disintermediation, non-repudiation, multiparty aggregation,

inter-organizational recordkeeping, change tracing, and data ownership. Blockchain could also provide a useful tool for managing and recording changes within a BIM model throughout the different construction phases and the lifecycle of a building. It could store an immutable public record of all the modifications in the model (Turk & Klinc, 2017).

3.5 Challenges and limitations

All of the benefits that are described in this chapter makes that people see a massive potential in the technology. Yet it is important to realize that these benefits come with certain challenges and limitations. Blockchain is at the current moment still in its early stage of development. In order to gain a wide adoption this technology needs to overcome certain challenges and limitations. Mthethwa (2016) described different challenges that are currently hampering the adoption of blockchain.

- **Awareness and Understanding**: The main challenge with blockchain is the lack of awareness and understanding around the subject. It is difficult for people or companies to adopt something that they do not entirely understand;
- **Security and Privacy:** Many blockchains used by cryptocurrencies like Bitcoin offer users the chance of using these platforms with pseudonymity. In this way people can use the platform without revealing their real identity. This introduces a problem to those applications that require the users real identity. Most applications need to ensure that an users identity is secured at all time. The concerns about security have a lot of impact on the acceptance of the technology. Though the most concerns come from the lack of understanding, because they should know that it is possible to make the blockchain suitable for any use case;
- **Regulations and Governance:** Regulations and governance always have a struggle to keep with the advances and improvements in technology, it takes a while for them to adapt and accept new technologies with regulations;
- **Scalability:** Normally, this is a very important concern in the development of any system. The Bitcoin blockchain can currently handles seven transactions every second. This could be a challenge for systems that require more transactions to be processed every second. For example VISA can currently handle approximately 2.000 transactions per second. This shows that the Bitcoin blockchain might not be scalable enough for some applications, yet some improvements can be made for it to work better. Also other type of blockchain or consensus protocols can be a solution for this problem;
- **Computing Power:** Blockchain is protected by an encryption algorithm and the miners are required to solve a mathematical problem. Once a miner submits a solution to the network a reward is giving to them in the form of newly mined coins. The main problem with mining is that a lot of computing power is needed to solve the mathematical problem. Because of this other consensus protocols have been introduced like ‘Proof of Stake’, they try to reduce the computational power.

3.6 Conclusion

In this conclusion the key features of blockchain technology are described. This will show an overview of all the capabilities of this new technology. A blockchain is basically a distributed database of records of all digital events that have been executed and shared among the participating parties. Each record in this distributed database is verified by consensus of the majority of the participating parties in the network. The concept of blockchain can be divided in some core characteristics. These characteristics explain the basic principles of blockchain technology.

Distributed: The records in a blockchain are distributed over the whole network. This means that every participant of the network will have the full data set. Every participant is responsible for its own part of the data, therefore there is not a single owner of the data.

Transparency: Every participant within the network holds the equal rights and abilities to access the ledger. The records are therefore transparent and traceable. The blockchain transparency comes from its nature since it is designed as a distributed network. Everyone that participates inside the network has a copy of the whole system. So there is one truth inside the network because everyone is working in the same dataset.

Immutability: The blockchain transparency aspect makes it also a robust network, since it is designed as a distributed network over the participants where each of these participants stores a copy of the whole ledger. When a transaction is verified by the blockchain, it is highly impossible to change or alter the transaction data. It becomes very difficult for an individual or any group of individuals to tamper with the ledger, unless these individuals control the majority (51%) of the participants of the network.

Security: Security measures are embedded in the network with no single point of failure, and they provide not only confidentiality but also authenticity to all activities. Anyone who wants to participate must use cryptography, opting out is not an option. And the consequences of reckless behaviour are isolated out to the person who behaved recklessly. The decentralised consensus on transactions is governing the update of the ledger by transferring the responsibilities to participants which independently verify the transactions. There is no central authority required to approve transactions.

This new technology creates opportunities for enhancing material passports. These opportunities are based on key features of blockchain technology. A blockchain can be used for the registration of any form of asset. In real estate the whole lifecycle of buildings can de digitalized and transferred on a blockchain. Blockchain technology can improve the transparency and traceability problems within material passports through the use of an immutable record of data, controlled user access, and the distributed storage. A shared, consensus based, and immutable ledger helps track the origin and the transformation of the product throughout the lifecycle of a building. The blockchain can create a registry enabling the identification and tracking of possession of a product throughout the supply chain. With regards to the challenge to determine the source of information within data systems can blockchain also play a role. It is a challenge within material passports to determine the validity of data that is stored in it. With blockchain technology a database or BIM models can be improved on the topics of confidentiality, provenance tracking, disintermediation, non-repudiation, multiparty aggregation, traceability of inter-organizational recordkeeping, change tracing, and data ownership. Blockchain could also be a useful tool for managing and recording changes to a database or BIM model throughout the different construction phases. Currently, there are still challenges and limitations for this new technology. In order to gain a wide adoption blockchain technology needs to overcome the following challenges; awareness and understanding, security and privacy, regulations and governance, scalability, and computing power.

4. Method empirical research

In the previous chapters the main characteristics of material passports and blockchain technology were elaborated on. Furthermore, the content and aspects of the information exchange system were described. Within the blockchain chapter the core characteristics of blockchain were described and the changes of blockchain technology within material passports were summed up. This chapter describes the method for the empirical research of this research. In the next paragraph the reasoning behind the type of research is explained.

4.1 Research approach

Within the introduction was described how the research design that is visible in figure 26 was created. Also the reasoning and theories behind this framework were described. Within this paragraph the research approach within the different parts of this research framework are elaborated further. A distinction was made between the two types of research, these are quantitative and qualitative research. Quantitative research is focused on quantifying data to be able to apply the results to a broader population. The used data in quantitative research are numbers that are suitable to be analysed statistically (Baarda & Goede, 2006). This study was based on a complex problem, it has not been studied much and there were little to no examples in practice. The focus of this research was on gaining more understanding of how blockchain technology could enhance the use of material passports. For this problem, in-depth information was needed, this type of information is mostly not suitable for statistical analysis. For this reasons, this research was based on a qualitative approach. A qualitative research is characterized by its iterative process (Baarda & Goede, 2006).

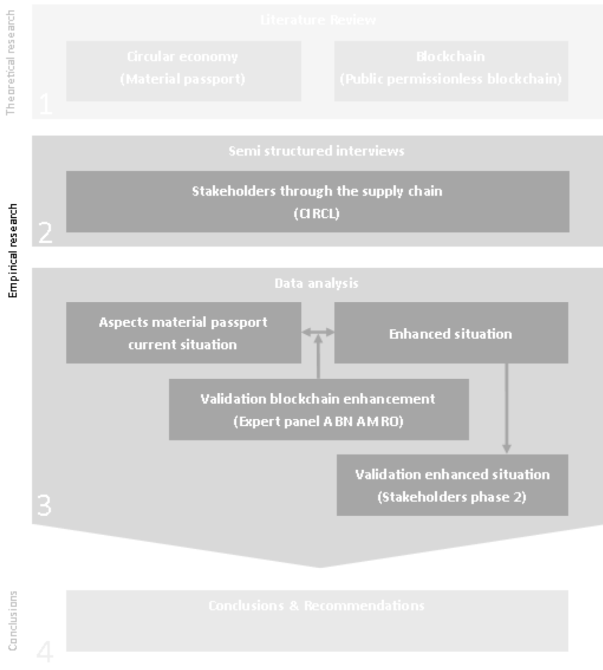


Figure 26: Research design (own illustration)

Baarda, de Goede, and Teunissen (2005) distinguish three types of research based on qualitative research, these are descriptive, testing and exploratory research. In qualitative descriptive research, it is about naming and inventing characteristic of the research units in terms of qualities, and not quantities. The second type is qualitative testing, this type is focused on the assessment of the usefulness and validity of a term. This term and the underlying theory is mostly funded with literature. Within qualitative testing the researcher tries to connect ideas to understand the cause and effect. The third type of research within qualitative research is qualitative exploratory research. In a qualitative exploratory research there is no theory in advance and there are no clearly formulated hypotheses available. Exploratory research is aimed on the development of a theory and or hypotheses, this type of research is applied to subjects where little research and knowledge is available (Baarda, Goede, & Teunissen, 2005). The type of research in this research was qualitative exploratory because there was no prior theory or clearly defined hypothesis available. Next to this there was also little to no scientific research and knowledge available on the link between the two topics. With regards to this study there was expected that blockchain technology could add value when it is implemented within material passports.

4.2 Empirical research

The second part in the research design is about the data collection within this research. In exploratory research there are different ways of collecting information. Baarda, de Goede, and Teunissen (2005) describe the three most commonly used methods of data collection as the use of existing documents, interviewing, and observation. Observation is a method that is used when the behaviour of participants need to be analysed, this is not the case in this study. Using existing information is mainly used to obtain information from events that have previously occurred in time, making it not suitable for this study because there were little practices available. Most existing information is discussed in the literature study. To get an answer on the research question information was needed based on experiences of the participants that have experience with material passports, therefore interviews were the most suitable method of data collection. Within interviews Baarda, de Goede, and Teunissen (2005) make a distinction between individual interviews and group interviews. In this study the most appropriate way of interviewing was the individual interview because the required information is about attitudes, knowledge, experiences, and opinions of individuals on the usage of material passports within the circular build environment.

Baarda, de Goede, and Teunissen (2005) describe that within semi-structured interviews the main topics and the main questions are fixed. The interviewer has to ask further questions when significant issues occur during the interview. Due to the explorative but specific topic of this thesis there was chosen to use semi-structured interviews. The goal of the interviews is specific, it was used to get information about the usage of material passports and what the points for improvement were. Therefore, they were also used to understand the barriers and requirements that were felt when using material passports. Thus, the interviews can be classified as focused semi-structured interviews. The population of the interviews were experts in the circular built environment at different locations in the lifecycle of a building that had experience with material passports, as was described in paragraph 2.4.3. With this interview was tried get a clear understanding of what the barriers were that could prevent the implementation of material passports. Also the requirements for the use of material passports were addressed in the interview.

The following three chapters go through part three of the research design (figure 26) and consist of the following parts; semi-structured interviews, validation blockchain technology, and validation enhanced material passport. In each chapter first the research approach is discussed and this is followed by the empirical findings. First the semi-structured interviews will be described. The semi-structured interviews provide qualitative data which were analysed further. All the interviews were transcribed, coded, and analysed afterwards. With these codes the different barriers and requirements were analysed. To get a clear understanding of how blockchain technology can address these barriers or fulfil these requirements an expert panel was conducted. This expert panel is described within the chapter validation blockchain technology. Within this chapter is analysed what barriers can be addressed and what requirements can be fulfilled with blockchain technology. Also the enhanced material passport with blockchain technology is described within this chapter. Because the enhancement with blockchain was made with experts from ABN AMRO another validation with the interviewees was held to validate if the new situations I really adds value. This validation is described within the chapter validation enhanced material passport. In this chapter is validated whether the improvement with blockchain technology is really an improvement compared to the current situation.

5. Empirical research: Semi-structured interviews

In the previous chapter the reasoning behind the chosen research method was described. Within this chapter the interview topics of the semi-structured interviews are determined which will lead towards the interview guide. After this the interview population will be presented and how the interviews will be analysed. The case that was used as a starting point for the interviews is also presented. In the second part of this chapter the empirical findings of the interviews will be presented.

5.1 Research description

As mentioned in the previous chapter the interview topics were based on the usage of material passports in circular projects. Within the interviews was analysed what barriers the different actors experience. Also the requirements for material passports were explored within the interview. There was specifically chosen to only address the material passport within the interviews. When those concepts are combined within one interview it is hard for the interviewee to give substantiated answers. Also finding experts that have experience with both material passports and blockchain technology was very difficult. For this reason was the interview only focussed on material passports. The connection with blockchain technology was made afterwards with an expert panel that consists of both blockchain as circular economy experts, this connection is described in chapter 6. Within this session was validated how blockchain technology could improve the concept of material passports. Table 6 shows different topics of the interview guide. The rows contain the different topics and the columns a description and the relevance.

Table 6: Topics interview guide

#	Topic	Description	Relevance
General introduction		Name interviewee, job description, business description.	To clarify the purpose of the research. It will also be used for shaping the context for the interview.
1	**Verification material passport**	This topic aims to clarify how a material passport is used through the lifecycle of a building. It also clarifies which barriers are seen in the market that could prevent the implementation of material passports.	It reveals what type of information is need by which actor. It is also used to validate the material passport as described within the theoretical framework. It will also reveal which barriers are felt within the market that could prevent the implementation of material passports.
2	**Material passport LLMNT**	The questions about LLMNT material passport will make the material passport specific with the information flows. It is also used to find out where the bottlenecks are felt inside the passport.	This section will clarify the process around the material passport LLMNT. Besides this it will show the bottlenecks within this process. This bottlenecks are the input for the improved situation.
Final question		The final question is about getting some additional aspects on the process that the interviewee wants to share. Also the different most important stakeholder in the process are exposed.	Exposes what the most important stakeholder is in the process of implementing material passports.

The different topics that are described in table 6 are supported by qualitative open questions based on the description of the topic in order to fulfil the relevance of the topic. The different supporting open questions per topic are shown in table 7.

Table 7: Topics interview guide and supportive open questions

#	Topic	Supportive open questions
1	**Verification material passport**	• Why is the use of a material passport important for your own process? • How is a material passport currently included in your own process? a. If not: How can you include material passports in your own process? b. What will be the added value? • Which barriers/opportunities do you currently see that could prevent/stimulate the use of material passports in your own process? a. Are these internal or external?
2	**Experience material passport (case CIRCL)**	• Was it clear what the purpose of the LLMNT passport was before you were asked to share information? • How was the process looking when you gave information to the material passport? How efficient was the process of providing the information? a. How would you improve this process in an optimized situation? • What barriers/problems did you experience when you give input to the material passports? a. Is this the same for all the data inputs? b. Are these barriers/problems internal or external? • What are the requirements for the data that you get as output from the system before you can use the data it in your own process? a. Is this the same for all the data outputs? • What opportunities do you see if you are able to use the information a material passport in your own process? • What are other important aspects of the system where material passports are stored?
Final questions		• Do you see some other barrier / opportunities for the implementation of material passports that are not mentioned yet? • Who are the most important actors in relation to the implementation of material passports?

The complete interview guide for the respondents can be found in appendix i. This guide contains the different topics and supportive open questions from table 6 and 7.

5.1.1 Interview population

Most of the interviews were structured around the case of the CIRCL pavilion. With this case the use of the material passport LLMNT was analysed from different sides. Besides this some interviews were also be held outside of this case. With these additional interviews the interview population was extended. This was done to ensure that the barriers and requirement based accidental events within the CIRCL project could be controlled with the interviews outside of this case.

5.1.1.1 Case CIRCL

The CIRCL pavilion by ABN AMRO is unique in the Netherlands. This is the first example of a building that has been built following a sustainable and circular design. Inside the building there is more than 2.000 m^2 of meeting and working space, it also contains a so-called 'living lab'. This is a space where the latest innovations, which seem promising but have not been proven yet, are applied and tested. For example, on the façade there is room that has been made suitable to test new materials, so it can been tested whether there are even more sustainable applications possible. For this living lab there is a collaboration with Delft University of Technology for monitoring and expanding the experiments. From an architectural perspective, the different lifecycles of the various parts of the pavilion has been explored. On the basis of this analysis the choice for certain materials were made (de Architekten Cie, 2017). Also the material passport LLMNT is included in this building. Figure 27 shows a picture of the project.

Figure 27: ABN AMRO CIRCL Pavillon (de Architekten Cie, 2017)

The different interviewees were mostly related to the CIRCL case. But some interviewees were not related to this case to control if they saw the same barriers and requirements. All the interviewees that are included are visible in table 8.

Table 8: Interviewees

#	CIRCL	Role	Sector
1	Yes	R&D mechanical engineer	Supplier
2	Yes	Associate	Designer
3	Yes	Director	Advisor
4	Yes	Group director sustainability	Contractor
5	Yes	Development director	Maintainer

6	Yes	Director	Urban Miner
7	Yes	Contract management maintenance corporate buildings	Facility Manager
8	No	Architect	Designer
9	No	Circular construction	Municipality
10	No	Project manager	Recycler
11	No	Advisor circular economy	Owner

5.1.2 Data analysis

The third part of this research (part 3 research design, figure 26) is about the interpretation of the data. In this phase the information from the different interviews was analysed. With the data from the interviews became clear what barriers and requirements were seen by the different interviewees when using material passports. The barriers and requirements were grouped in five clusters regarding the data storage addressed by Damen (2012). The five clusters are: provision, storage, access, quality, and presentation of the information and were described in paragraph 2.5.6 of this report. The five clusters were also used as codes for analysing the interviews. During the interviews the clusters were used to challenge the interviewees if all the barriers or requirements were covered. Besides the five clusters for the requirements of the information exchange system there was also focussed on the process of how the material passport was used. Therefore, process was the sixth code in analysing the interviews. In table 9 the different codes are shown.

Table 9: Clusters interview

Information Exchange Material passport	Exchange system	Provision of the information
		Storage of the information
		Access of the information
		Quality of the information
		Presentation of the information
	Process	Process of giving information

With these codes was analysed in what area the barriers and requirements could be placed. These different barriers and requirements were analysed to get a clear picture of how the material passport could be improved

From the interviews it became clear that besides the barriers and requirements also the opportunities could be placed in these six different clusters. The different barriers, opportunities and requirements were all clustered in different clusters. Afterwards groups of the different answers were made within the clusters. These groups resulted in the complete codebook. This codebook is visible in table 10. In appendix iii the different codes are connected to the different interviewees.

Table 10: Codebook interviews

Viewpoint	Clusters	Code
Opportunities	Provision of the information	More data continuity Cost reduction
	Storage of the information	-
	Access of the information	-

	Quality of the information	Better data management Clear options for reuse Determining real value Solving warranty issue
	Presentation of the information	More uniformity
	Process of giving information	Information request at the beginning
Barriers	Provision of the information	Costs of providing Data not available Companies do not want to be transparent No overview lifecycle building Confidentiality issues
	Storage of the information	Who has ownership?
	Access of the information	Who has access?
	Quality of the information	Quality assurance No definition material passport
	Presentation of the information	Lack of uniformity
	Process of giving information	Not involved from the beginning No experimentation
Requirements	Provision of the information	Easy handling Reward system Cooperation supply chain Only necessary information Predefined levels of detail
	Storage of the information	Clear ownership data One data source Security
	Access of the information	Predefined who has access
	Quality of the information	Validation Immutable Dependencies Traceability Dynamic during the lifetime
	Presentation of the information	Uniformity
	Process of giving information	Added value has to be clear

In this paragraph the structure of the interviews was discussed. Also the different interviewees and the case for the interviews were discussed. All the interviews were transcribed and coded. On the basis of these codes were the interviews analysed and was determined what the most important aspects were. In the next paragraph the empirical findings from the interviews are discussed. Based on these findings is in chapter 6 an improved situation described. This improved situation was validated with an expert panel from ABN AMRO to ensure that it was realistic. As last was the improved situation also validated by some of the interviewees. This is described in chapter 7.

5.2 Empirical findings interviews

In this second part of this chapter the empirical findings from the interviews will be presented. Within the interviews several subjects were addressed regarding material passports. First the verification of the material passport was done. Within this paragraph is analysed how material passports are implemented within the core process of the companies of the different interviewees. Also the opportunities are described when material passports are implemented. After this the barriers are described that are felt when providing the information to the material passport. Also the requirements are described for the system where the material passports are stored before the interviewees will use the information within their own process. The opportunities, barriers, and requirements were clustered within the following six clusters: provision, storage, access, quality, presentation, and the process of giving information. The order of describing the different aspects correlates with how many times this aspect was mentioned during the interviews. The most important aspects are therefore mentioned first followed by the other aspects. The full coding scheme is visible in appendix iii.

5.2.1 Verification material passport

Material passports are, according the majority of the interviewees, important for their own core process. It will give them an insight in where their products are stored and what the current state is. Currently, there is a data loss between the different stages of the lifecycle of a building. It is stated that companies currently do not know what they own. Also there is currently no insight in the specific material flows that go in and out of a building. The material passport is recognised as a tool to overcome this data loss and creates a more consistent data flow. Especially companies that have responsibilities over different stages of the lifecycle are noticing the added value of material passports. The different interviewees see material passports as a central place to store the data from a building. Also the function of a material passport regarding the trend towards urban mines is seen as important. When in the future more materials are reused the information within the material passport is seen as an important enabler.

The material passport is recognised by most of the interviewees as an important tool to get insight in the information streams during the lifecycle of a building. But at this moment it is not yet implemented widely. The concept of material passports is still in its infancy. The interviewed companies are all recognising its potential and importance, but only a few having a working material passport at this moment. Companies are currently experimenting to find out what the best format and content is. The LLMNT material passport is also still in its development phase and will evolve in the coming projects to its most optimal. Within these projects the passport will be used on other buildings.

In figure 28 is visible how the process was structured for providing information to the LLMNT material passport. The database where the passport is stored is owned by one trusted company, all the users of the passport trust this company with their information. All the different users have access to this database specified to their rights.

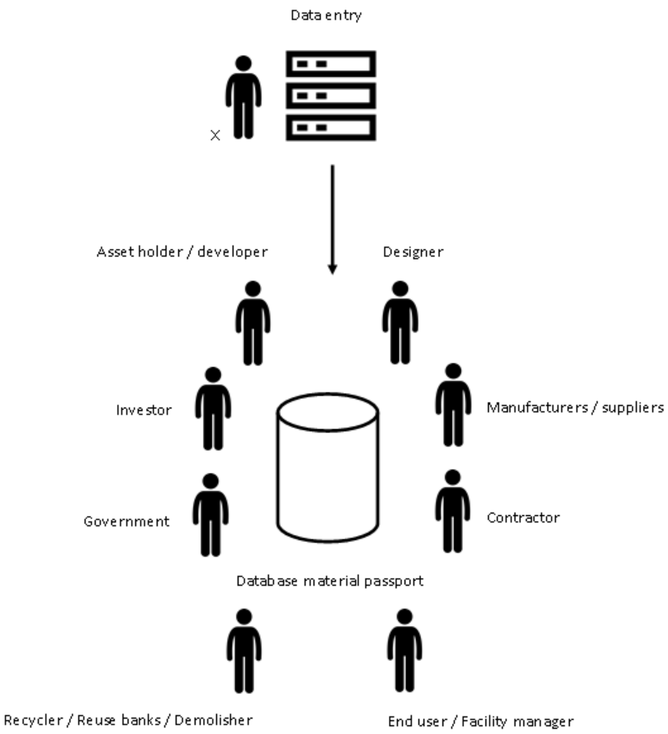


Figure 2 ... stration)

5.2.2 Most important actors

Within the interviews the most important actors regarding the implementation of material passports were discussed. Especially the owner of the building and the government were addressed as important actors. The owner is seen as an important actor because he owns the asset. He is responsible for the asset and therefore has an incentive to keep the data in good quality. The government was often mentioned in relation towards regulations. According to the interviewees, regulations are set out by the government and owners of assets will follow within this direction. The bank was also mentioned as an important actor. If banks obligate material passports when financing, then the market will immediately feel an financial incentive to use the passports.

5.2.3 Opportunities material passport

There were different opportunities seen by the interviewees for material passports. Those opportunities were clustered within the six clusters that were described previously. The opportunities that were mentioned are regarding the implementation of material passports. These opportunities show the potential of material passports when these are widely used. It also shows the potential when the barriers are taken away or the requirements are fulfilled, which are described later this chapter. The clusters with the opportunities are visible in table 11. Also is visible in this table which interviewee sees what opportunity. The different opportunities will be addressed in this paragraph.

Table 11: Opportunities material passport

Opportunities

Cluster	#	Covering code	Supplier	Architect I	Architect II	Advisor	Contractor	Maintainer	Facility manager	Owner	Urban Miner	Recycler	Municipality
Provision of the information	1	More data continuity					x			x			
	2	Cost reduction								x			
Storage of the information													
Access of the information													
Quality of the information	1	Improved data management	x			x		x	x	x	x	x	x
	2	Clear options for reuse					x		x	x	x		x
	3	Determining real value		x			x				x	x	
	4	Solving warranty issue		x	x		x	x					
Presentation of the information	1	More uniformity	x		x							x	
Process of giving information	1	Information request at the beginning	x								x		

Provision of the information

More data continuity: The first opportunity that was seen is about the data continuity. The material passport is seen as tool to improve the data continuity between the different stages in the lifecycle of a building.

> *"When a building is transferred to facility management often all the information is lost, not just parts but all of it. They just start over again."*

The interviewees see the material passport as a tool to overcome this gap by working with the same dataset throughout the whole lifecycle of a building.

Cost reduction: Another opportunity that was seen by one interviewee is the possibility of cost reduction. Once all information is collected one time correctly, it can save money compared to collecting specific information for your own process each time that you need it. A lot of data is collected over the lifetime of a building, when this data is collected one time properly then all the participants have an advantage from this.

Storage of the information

Within the cluster storage of the information no opportunities were seen by the interviewees.

Access of the information

Within the cluster access of the information no opportunities were seen by the interviewees.

Quality of the information

Improved data management: The first opportunity within the cluster quality of the information was seen by almost all of the interviewees. This opportunity is about the improvement of the data management during the lifecycle of a building. Currently, information about owned assets is not always available for every company that is involved in the process.

> *"In a project you first have to make an inventory of what there is and what you have before you can make a plan. If there is a data system that contains everything, that saves you an incredible amount of work, time, and knowledge loss."*

Every company has its own datasets and works with its own information. Also within companies different sets of data are created about the same assets. Material passports could create one set of data that is available for everyone. When all this information is available for everyone also the core processes of companies could be improved.

Clear options for reuse: This opportunity was seen by five of the eleven interviewees. Both the possibilities for reuse and the information about the extraction of materials from buildings are seen as important aspects regarding the reuse of materials. Without the information about how the materials can be extracted from a building, the information about the reuse possibilities of materials has no value.

Determining real value: Another opportunity that was seen when information about materials is available is that the value of these materials will increase compared to the materials that have no information available about their reuse possibilities. Also the real value of these materials will become clear when this information, condition, and value is always available.

> *"So it should help you understand eventually real values."*

When this information about all the owned materials and assets is available, than for example no due diligence is needed anymore. There is always an insight is what the real value is of the owned assets.

Solving warranty issue: The last opportunity that was seen within this cluster is knowing the possibilities for giving warranty. Besides the value of materials, the material passport can also play a role in the problem about the warranty of used materials. For an architect the warranty can be a problem when they design a building with used materials. When warranty of products and materials is really important for a client the material passport can be a possible solution. When you know what the story is behind a material, the consideration can be made if the material can fulfil another lifetime of a building.

> *"When you can read in a report that there had been no damages, or that they had been repaired properly. That is just like buying a car at a market place and the service book is included. You will have a different feeling when you know its history."*

Presentation of the information

More uniformity: Currently there is no uniformity in the information that is used during the lifecycle of a building. Different companies that are involved use different standards to structure their data. An opportunity for the material passport that was seen by three interviewees is that the material passport can create more uniformity throughout the lifecycle of a building. This uniformity can be created because all the companies that are involved have access to the same dataset.

> *"The more uniform the better."*

The topic uniformity is also addressed under the barriers and requirements. Every interviewee has under one of the different groups addressed that uniformity of the information within the lifecycle of a building is important for the material passport.

Process of giving information

Information request at the beginning: There was addressed by two interviewees that it is important that the information request for the material passport is done at the beginning of a project. It is really hard to collect all the information afterwards. Also the suppliers have no incentive anymore to provide all the requested information. When the information request is done during the negotiation phase of a project, than the client has control and the supplier has an incentive to provide it.

5.2.4 Barriers material passport

Within the interviews there was also a focus on finding the barriers that are felt when using material passports. These are the barriers that could prevent that companies provide the requested information for the material passport. This are also the barriers that could prevent a wide implementation of material passports because the material passport is only useful when its filled with correct and up-to-date information. In table 12 the different barriers that were addressed during the interviews are presented.

Table 12: Barriers material passport

Barriers

Cluster	#	Covering code	Supplier	Architect I	Architect II	Advisor	Contractor	Maintainer	Facility manager	Owner	Urban Miner	Recycler	Municipality
Provision of the information	1	Costs of providing	x	x	x	x				x			x
	2	Data not available		x			x		x		x	x	
	3	Companies do not want to be transparent	x	x				x					
	4	No overview lifecycle building					x	x					
	5	Confidentiality issues	x										
Storage of the information	1	Who has ownership?			x			x		x			x
Access of the information	1	Who has acces?	x			x				x			
Quality of the information	1	Quality assurance			x			x		x			
	2	No definition material passport		x			x						
Presentation of the information	1	Lack of uniformity	x			x	x		x	x			x
Process of giving information	1	Not involved from the beginning		x							x		
	2	No experimentation								x			

Provision of the information

Costs of providing: The barrier that was mentioned by most of the interviewees is about the costs for providing the information. For the provision of the initial information of the material passport costs have to be made up front.

> *"I have to describe it, so it just takes time and costs money. It is sometimes just as banal as ordinary money."*

Because of the long lifetime of buildings it will take some years before the initial investment will be earned back. At this moment the incentive for providing the information is not clear yet. This was seen as a barrier by the different interviewees.

Data not available: The second barrier that was mentioned is about that the requested information for the material passport is not available.

> *"I cannot find all the original data of those materials."*

Especially for existing buildings it will be a challenge to provide all the specific information. It often happens that suppliers of the products within existing buildings have gone out of sight. When this happens it is almost impossible to provide all the specific information. Also for companies such as urban miners it is hard to provide all the specific information about their products for this reason.

Companies do not want to be transparent: Not all the companies that were interviewed mentioned that they want to be fully transparent about their products.

> *"Our competitors do not share that data. This is a competing market and everyone has their own technology."*

Especially in high competitive markets not all companies want to become fully transparent and give insight in everything about their products. The material passport requires some level of transparency.

No overview lifecycle building: The overview regarding the data that is needed during the whole lifecycle of a building was seen as a barrier. As described earlier the data continuity is seen as an opportunity for the material passports when these are widely implemented. The lack of overview is seen as a barrier for the implementation. Material passports needs to include all the necessary information before it is used throughout the whole lifecycle of a building. The information request has to be done at the beginning of the project because otherwise it is hard to fill the passport at a later stage with all the necessary information. As there is currently a lack of continuity between the different stages of the lifecycle of a building, there is no clear vision about what the content needs to be of the material passport.

Confidentiality issues: Confidentiality issues were seen as a barrier for material passports from the supplier side. They are restrained with providing information because it is not clear who will use the information and if confidentiality agreements can be signed. Especially in high competitive markets information is kept inside a company or under embargos. With material passports the information about materials and products can become public, this was seen as a barrier for providing the information.

Storage of the information

Who has ownership?: Within the cluster storage of the information the ownership of the data was seen as a barrier. This barrier is about who becomes the owner of the data within the material passport. Specific data about materials during the lifecycle of a building gives a company power.

> *"The ownership rights could be one of those barriers."*

It is possible that companies do not want to provide the data when someone else becomes the owner of that data. Also the information from sensors within a building raises questions about who the owner of this information is. This question is also asked regarding the responsibility to keep the data up-to-date. The owner of the data has an incentive to keep the data up-to-date.

Access of the information

Who has access?: The barrier regarding the access of the information is about the access and level of detail of the data. The access of the data is about who can see and use the data that is stored within the material passport. Some interviewees experience a problem when the data is open to anyone. Therefore, they like to see different access levels to see specific data. In line with this is the discussion about what level of detail will be open to the other users or public that use the passport.

Quality of the information

Quality assurance: The most mentioned barrier within this cluster was about how to manage the quality assurance of the data within material passports. Different interviewees addressed that the material passport is as good as the information that is stored in it.

"Garbage in is garbage out."

They see the necessity for good data as a barrier for the material passport. If for example the information not is updated frequently, then the materials passport will lose its value. Within this barrier the question arises about who is responsible for the consequences when the data is not correct.

No definition material passport: Another barrier that has impact on the quality of the information is that there currently is no standard definition what a material passport is.

"We are looking for some kind of standard."

Different initiatives have started but those initiatives have all their own focus. No prescribed format about what the content needs to be for the material passport was seen as a barrier. Also the knowledge gap about what information is really needed has influence on the quality. At this moment there are different perspectives within the market of what a material passport is and what the content needs to be. This creates indistinctness that does not stimulate the quality of the information inside the material passport.

Presentation of the information

Lack of uniformity: The lack of uniformity frequently came forward within the interviews as a barrier for the implementation of the material passport. The lack of a standard for data within the built environment was seen as a barrier for the wide adoption of material passports as everyone uses their own language. At this moment the information from different actors within the built environment will not fit onto each other.

Process of giving information

Not involved from the beginning: The first barrier that was seen is about not being involved from the beginning of the process when the material passport is filled. As a supplier you need to be involved from the beginning in order to provide all the information. It is addressed that when they are not involved from the beginning it is hard to provide all the requested information.

No experimentation: The other barrier is about experimentation. One interviewee addressed that experimentation is needed to gain experience with the concept of a material passport. It is also important that companies provide the requested information in order to get experience about what information is really needed. It is common in the built environment to push the real experimentation to the future and do a lot of desk research about a certain topic. To get wide implementation experimentation is more important than doing research about it. This because the real bottlenecks only become known when you apply the material passport in real projects.

5.2.5 Requirements material passport

Besides focussing on the barriers there was also a focus on finding the requirements for material passports in the interviews. With the requirements was analysed what aspects need to be included in the system where the material passports are stored, before the different interviewees use and trust it. This will result in acceptance and usage of the system and the material passport. The different requirements are visible in table 13.

Table 13: Requirements material passport

Requirements

Cluster	#	Covering code	Supplier	Architect I	Architect II	Advisor	Contractor	Maintainer	Facility manager	Owner	Urban Miner	Recycler	Municipality
Provision of the information	1	Easy handling	x	x					x				
	2	Reward system				x					x		
	3	Cooperation supply chain				x		x					
	4	Only necessary information									x		
	5	Predefined levels of detail	x										
Storage of the information	1	Clear ownership data	x	x									
	2	One data source								x			
	3	Security	x										
Access of the information	1	Predefined who has access	x						x				
Quality of the information	1	Validation		x		x			x	x	x	x	
	2	Immutable		x		x							
	3	Dependencies					x				x		
	4	Traceability									x		
	5	Dynamic during the lifetime		x									
Presentation of the information	1	Uniformity	x				x	x	x	x			
Process of giving information	1	Added value has to be clear	x			x							

Provision of the information

Easy handling: Easy handling of the system was addressed by most of the interviewees as an important requirement for material passports. The passport need to be accessible in an easy way in order to keep the data up to date. The people that do for example the maintenance for a building need to use the passport in such way that the information inside it stays up to date. A lot of values inside the passport are dynamic, such as the real value of materials. This need to be updated in such way that the value of a material always represent the correct real value.

Reward system: The second requirement that was mentioned is about the reward system that could stimulate the provision of the requested information. The companies that give valuable input to the material passport should be rewarded for their work. They have to do extra work compared to the other companies, this was also seen as a barrier.

Cooperation supply chain: Another requirement that was seen by different interviewees is that cooperation within the supply chain is important. It is necessary that material passports are adapted by the whole supply chain in order to fill them with the correct information. Companies need to get the mind-set that they want to share information for the greater goal of a circular economy. They must also have the courage to be open and share the information. Currently this mind-set is not present within the whole supply chain.

Only necessary information: For suppliers it costs time to provide all the information, therefore they addressed that it is important to only ask for the necessary information.

> *"There is no point at all in very detailed information. I think that an important part of the register does not have to be linked to that material at all. This register is known at the wholesaler, distributor, or supplier itself as it also is with other goods."*

There was addressed that some passports are so detailed in their information request that that the core functionalities (reusing materials) are not reflected anymore. If the information request is just adapted to the core functionalities of the passports such as reusing materials, it will also be easy to fill them and keep them up to date.

Predefined levels of detail: Another requirement that was mentioned is about the predefined levels of detail for the information. For a supplier it is not always possible to give all the detailed information. It has to be clear on which level the information will be shared.

> *"It is more like a compromise about how much detail you want and how much detail we want to share. That should be a compromise, somewhere in between."*

Also different levels of information detail will help for this when the information that is stored in the passport is only shared on a more abstract level with the other users.

Storage of the information

Clear ownership data: Within the storage of the information it has to be clear who the owner is of the data. For a supplier a non-disclosure with the owner of the data can for example be important. But also the data from sensors raises questions, who will be the owner of this data? With the question about the ownership also the question about who is responsible for the data is important. It has to be clear for the users of the material passport who is responsible for what data.

One data source: Also one data source was addressed as an important topic. When the data in the passport is linked to the original data source the chances for errors are the smallest. Also the perception about for example the toxic level of materials can change. For example, asbestos was some years ago a commonly used material within buildings. But now it is marked as highly toxic. With scenarios like this you want to change a material like asbestos with one click in all the material passports from a normal material to highly toxic in order to not miss any toxic products when the dismantling of buildings starts.

Security: Last the security of the data was also seen as important. The information in the material passport need to be secured in a good way. The information within the material passport can be sensitive, it can represent the ownership of someone. Also the information from suppliers are not meant for everyone. Therefore, the security has to be in such way that the specific information is not available for everyone. Also different levels of access will help for this requirement.

Access of the information

Predefined who has access: The requirement within the cluster access of the information is additional to the last requirement from the previous cluster. It has to be clear which company has access to which level. Not everyone need to see all the specific information about materials and products.

Quality of the information

Validation: The requirement that was addressed the most within this cluster is the validation of the information. The data in the material passport needs to be correct and up to date. In order to trust all the data some sort of validation is needed. Within this validation it has also to be clear how precise the data is. The data can for example be measured in the work or within laboratorial conditions, this has to be clear to prevent that decisions are based on for example assumptions. This data quality has to be reported in the material passport.

Immutability: Also the immutability of the data was recognised as an important requirement. When the data is stored within material passports it must be seen as the truth. Therefore, it needs to be trustworthy data. If adaptions are made within the data then this must be visible for everyone, with this the evolution of the data set becomes visible. This will create trust in the information within the material passport.

Dependencies: The dependencies between the different materials were also mentioned as an important requirement. If a material has a high value but it cannot be extracted from the building, then it does not represent this high value.

> *"It is nice to know that there is a front in the basement. It is also nice to know that the front has a certain size. But if the hole to get it out is smaller than the front, then it does not come out like a front anymore."*

It has to be clear how materials are attached to each other and how they can be taken out. This will also be helping in understanding the real potential for reusing materials.

Traceability: Also traceability was seen as an important requirement. It has to be clear where materials went in their previous usage or lifecycle. The information need to be attached to a material, so when a material changes from building there can be prevented that information get lost.

Dynamic during lifetime: And finally the model has to be dynamic through its lifetime. A building changes from day to day with its maintenance, therefore the material passport need always represent the current state of the building. All the mutations inside the building need to be included in the material passport in order to keep its value. If the information within the material passport is outdated, it will not be used anymore.

Presentation of the information

Uniformity: For the material passport it is important that the whole built environment speaks the same language, some form of uniformity is needed. This is also mentioned within the opportunities and barriers.

> *"The uniformity within the data is also very important."*

Currently there is no uniformity in the data during the lifecycle of a building. The material passport needs this uniformity to work effectively, but it is also seen as a driving force for creating the uniformity.

Process of giving information

Added value has to be clear: Before companies will give information to the material passport it has to be clear what the added value will be.

> *"If we want something from a supplier we simply oblige him in the information request with a penalty clause when he does not disclose the information. But that is not motivating the supplier to share information, that is forcing him by compulsion and urgency."*

Companies will not provide the information when it is not clear what the added value is. This can be the added value within the roadmap towards a circular economy but also the added value for the business case when the material passport will make instead of cost money. There is not one added value for material passports.

5.2.6 Relation between opportunities, barriers, and requirements

Within the previous paragraphs the different aspects under the opportunities, barriers, and requirements by the interviewees were discussed. A relation can be seen between these different viewpoints, what was emphasized as a barrier by one of the interviewees could be described as a requirement by another. Therefore, all those aspects are combined in table 14. Within this table the different opportunities and barriers are combined with the requirements. This gives an overview of all the aspects that were mentioned during the interviews. Within this paragraph is also discussed why some aspects can be combined to make a comprehensive list of aspects for the material passport. In appendix iv the extended table is visible where is visible how the opportunities, barriers, and requirements are combined.

Table 14: Aspects material passport

Aspects	#	Covering code	Supplier	Architect I	Architect II	Advisor	Contractor	Maintainer	Facility manager	Owner	Urban Miner	Recycler	Municipality
Provision of the information	1	Reward system	x	x	x	x				x	x		x
	2	Only necessary information		x			x	x	x		x	x	
	3	Easy handling	x	x					x				
	4	Confidentiality	x	x				x					
	5	Cooperation supply chain				x		x					
	6	Data continuity					x			x			
	7	Standardisation		x			x						
	8	Predevined levels of detail	x										
Storage of the information	1	Ownership data	x	x	x			x		x			x
	2	One data source								x			
	3	Security	x										
Access of the information	1	Predefined who has access	x			x			x	x			
Quality of the information	1	Validation		x	x	x		x	x	x	x	x	
	2	Data management	x			x		x	x	x	x	x	x
	3	Real value					x		x	x	x	x	x
	4	Immutable		x	x	x	x	x					
	5	Traceability									x		
	6	Dynamic during the lifetime		x									
Presentation of the information	1	Uniformity	x		x	x	x	x	x	x		x	x
Process of giving information	1	Added value has to be clear	x			x							
	2	Information request at the beginning	x								x		
	3	Experiment								x			

Provision of the information

Reward system: The aspect of a reward system within material passports was given during the interviews as a requirement. Under this requirement lays the barrier that companies have to make costs to provide the requested information. Some interviewees told that the companies that provide information need to make initial costs, this can be seen as barrier. The reward system is a possible solution to overcome this barrier.

Only necessary information: The aspect to only ask for necessary information in the material passport was seen as a requirement and is contributed by some barriers that are based on the same view. The barriers about that the data is not available and that there currently is no overview of what information is necessary during the lifecycle of a building were also implying that only the necessary information needs to be included within the material passport.

Easy handling: Easy handling was a requirement that was mentioned by the interviewees. But this requirement was not backed by other opportunities or barriers in the conducted interviews.

Solving confidentiality: The aspect confidentially of the information was seen as a requirement for material passports and comes forward out of the barrier about that not all companies want to be transparent. If a company does not want to share all its information it creates confidentiality agreements with other companies that use the data.

Cooperation supply chain: Cooperation of the whole supply chain was a requirement that was given by the interviewees. But this requirement was not backed by other opportunities or barriers in the conducted interviews.

Data continuity: Data continuity and cost reduction are both opportunities that were mentioned during the interviews. Both opportunities lay in the extension of each other. The data continuity is about that the data is available within all the stages in the lifecycle of a building. The cost reduction is regarding the aspect that if the data is collected one time good the investment will be lower than collecting it specifically for each project during the lifecycle of a building. This implies that collecting the data one time properly will also lead to a cost reduction.

Standardisation: Within the interviews the lack of a definition of what needs to be included within the material passport was mentioned as a barrier. This implies that the market wants some form of standardisation for material passports. Therefore is standardisation an important aspect for the wide adoption of material passports.

Predefined levels of detail: Predefined levels of detail of the information within the material passport was mentioned as a requirement during the interviews. But this requirement was not backed by other opportunities or barriers in the conducted interviews.

Storage of the information

Clear ownership data: The ownership of the data was mentioned was an important requirement. It has to be clear who the owner is of what data, and with the ownership comes also the responsibility for keeping the data up-to-date. The ownership of the data was also seen by the respondents as a barrier to provide the information. This barrier lays in line with the requirement about that it needs to be clear of who the owner is.

One data source: One data source was a requirement that was given by the interviewees. But this requirement was not backed by other opportunities or barriers in the conducted interviews.

Security: Security of the information was a requirement that was given by the interviewees. But this requirement was not backed by other opportunities or barriers in the conducted interviews.

Access of the information

Predefined who has access: The interviewees mentioned that determining who has access to the data an important aspect is. This creates the requirement that it has to be clear who has access to the data. A barrier that could prevent the provision of the information was that it is not clear who can see and use the information that is stored inside the material passport. This implies that this barrier can be taken away when there is up front predefined who has access to the information.

Quality of the information

Validation: The validation of the information was seen as an important factor by the interviewees. The material passport is as good as the quality of the data that is stored in it. The interviewees prefer a validation because it is a control mechanism on the quality of the data. Quality assurance was seen as a barrier for material passports because it is hard to manage this control mechanism. This barrier lays therefore in line with the validation that was mentioned as a requirement. The validation of the material passport has to be done in a executable and realistic way.

Data management: The data management of the information was an opportunity that was given by the interviewees. But this opportunity was not backed by other barriers or requirements in the conducted interviews.

Real Value: Knowing information about the real value of materials or products was seen as an opportunity for material passports. This real value can only be determined if the options for reuse and the dependencies between materials are included within the material passport. The dependencies between the materials were seen as a requirement for the material passport and the options for reuse was seen as an opportunity. These three factors come together in the aspect of real value of materials.

Immutable: Immutability was seen as a requirement by different interviewees. This requirement lays in line with the opportunity of solving the warranty issue that was mentioned within the interviews. The material passport can be used as a solution for the warranty issue that occurs for reused materials. This will only work when the users of the material passport have the certainty that the information within the material passport is correct and immutable. Therefore lays the opportunity of warranty in line with the requirement about immutability.

Traceability: The traceability of the materials was seen as an opportunity by the interviewees. But this opportunity was not backed by other barriers or requirements in the conducted interviews.

Dynamic during lifetime: The material passport needs to be dynamic during its lifetime. This was seen as a requirement by the different interviewees. But this requirement was not backed by other opportunities or barriers in the conducted interviews.

Presentation of the information

Uniformity: The aspect of uniformity was mentioned as an important aspect within the opportunities, barriers, and requirements during the interviews. The material passport is seen as a possible solution to create more uniformity during the lifecycle of a building. But the current lack of uniformity in the data within the built environment is also seen as a barrier for material passports. Therefore, uniformity is seen as a requirement for the success of a wide implementation of the material passport.

Process of giving information

Added value has to be clear: Within the different interviews was addressed that a requirement for the material passport was that the added value has to be clear in order to have an incentive to provide the required information. This requirement was not backed by other opportunities or barriers in the conducted interviews.

Information request at the beginning: The information request for filling the material passport has to be done at the beginning of a project. This requirement was backed by the barrier that some interviewees told that the information request was not done at the beginning of the project and that it was therefore difficult to provide all the requested information.

Experiment: One of the interviewees told that it was important to experiment. The lack of experimentation was seen as a barrier for the material passport. This barrier can be turned to the aspect that experimentation is important for the implementation of material passports.

Within this paragraph a comprehensive list of aspects for the information exchange system where material passports are stored is made. This comprehensive list is used to make the link in the next chapter (chapter 6) with the public permissionless blockchain. In that chapter the characteristics of this blockchain are connected to the different aspects of the information exchange system.

5.3 Conclusion and discussion semi-structured interviews

The interviews that were held were structured around the lifecycle of a building. Actors from the initiative, construction, maintain, and reuse phase were included within these interviews. The interviews were structured in such way that the first part was based on the verification of the material passport. Based on the answers of the different interviewees it can be stated that they recognize the material passport as an important tool to improve their own process. Within the interviews was stated that there currently is a data loss between the different stages of the lifecycle of a building. The interviewees recognise the material passport as a potential solution towards this data loss.

The most important actors regarding the implementation of material passports were also discussed. Especially the owner of a building and the government were addressed as most important actors. The owner is seen as import because he is the owns the asset. He is responsible for the asset and therefore has an incentive to keep the data in good quality. The government is often mentioned in relation to regulations. The bank was also mentioned as an important actor. If banks oblige material passports for financing, then the market will feel immediately an financial incentive to use the passports.

Finding the opportunities for material passports was also part of the interview. The interviewees recognised different opportunities that could stimulate the use of material passports. The wide implementation of material passports could stimulate the data continuity within the market. This can lead to a cost reduction because all the data is collected properly at once instead for every project. This will result in better data management throughout the lifecycle of a building. The material passport will also be used to determine the real value of materials and can be a helpful tool in providing some sort of warranty for used materials. The opportunities for reusing materials are become more clear when more data is available about them. Most of these opportunities were also recognised in the research of Debacker and Manshoven (2016).

Aside from the opportunities the barriers were also addressed during the interviews. The interviewees recognised different barriers regarding the provision of the information. The cost of providing the information, the confidentiality of data, and that not every company wants to become transparent were seen as potential barriers. Debacker and Manshoven (2016) describe that the intellectual property of material and product related data is seen as a barrier. Balancing intellectual property on material and product related data with open source data remains a challenge but is necessary for the success of material passports. Another barrier that was mentioned in the interviews was that the requested data within the material passport is not always available, especially when the materials are extracted from existing buildings. Also determining the ownership of the model is important. This includes the responsibility for the quality of the data and keeping it up-to-date. Currently, there is no standard definition of what needs to be included inside a material passport. Therefore, the lack of uniformity is also seen as a barrier. This last barrier was also described in the research of Debacker and Manshoven (2016).

Confidentiality is stated by different authors as one of the major barriers for information sharing (Damen, 2012; Smith, Watson, Baker, & Pokorski II, 2007; Lee & Wang, 2000). Within the interviews confidentiality was only mentioned by three interviewees. This illustrates that the barrier was seen in contrast to the literature not as most important. A possible explenation for this is that the described opportunities, barriers, and requirements are perceived aspects because the material passport is still in its immature phase. This could affect the aspects that were mentioned because the answers are not always based on a long track record of experiences.

The requirements of the system where material passports are stored were also addressed during the interviews. Different interviewees stated that rewarding the companies that provide the information for the material passport is important because this is an incentive for receiving correct information. Therefore, cooperation within the whole supply chain is needed. It is stated that only the necessary information should be included in the passport, this will also improve the easy handling of it. The ownership of the data is an important topic that needs to be clear. This is important with regarding to keeping the data correct and up-to-date. Also the linkage to one data source could help to stimulate this. When the data is stored within every passport on itself, it is hard to keep it updated at every location. With the storage also the security is addressed as an important requirement. Regarding the quality of the information is validation, immutability, and traceability addressed as important requirements. The system must also be dynamic during the lifetime of the building. Finally, uniformity was addressed as important for the information within the material passports.

In the interviews the different aspects related to opportunities, barriers, and requirements were analysed. Those aspects based on the opportunities, requirements, and barriers were combined to make a comprehensive list of aspects that were seen as important for the material passport. With this list could be determined what aspects can be addressed with blockchain technology.

6. Empirical research: Validation blockchain enhancement

Within the previous chapter the outcomes from the different interviews were discussed. Within this chapter the link with blockchain technology is made. This connection with blockchain technology was validated with an expert panel. Also the material passport enhanced with blockchain technology is presented, this enhanced situation was also validated by the expert panel. The interviews were focussed on material passports because connecting material passports with blockchain technology within one interview would be too complex. For this analysis the characteristics of the public permissionless blockchain were used as described in chapter 3.

6.1 Research description

Not all different aspects that were discussed within the interviews can be addressed with blockchain technology. Within this paragraph is addressed which aspects for material passports have a relation with blockchain technology in order to determine how blockchain can fulfil those aspects. Based on those aspects can be concluded whether the public permissionless blockchain is a useful technology to improve material passports by either taking away these barriers or fulfil these requirements.

6.1.1 Expert panel

To get a realistic image of how blockchain technology can be used an expert meeting with some blockchain experts inside ABN AMRO was conducted. This expert panel was used to validate the aspects of how blockchain technology can improve the concept of material passports. In table 15 the different experts are presented. Within this meeting was analysed which aspects can be addressed with blockchain technology. Finally the improved situation was created during this meeting.

Table 15: Expert panel

#	Name	Role
1	Merijn Zaat	Innovation Manager (Blockchain Technology)
2	Stephan Hagens	Innovation Manager (Experiment Expert)
3	Bo Daalmans	Innovation Manager (Blockchain Technology)
4	Alexa Krayenhoff	Innovation Manager (Circular Economy)
5	Emma Cherim	Innovation Manager (Service Designer)

6.2 Empirical findings blockchain enhancement

Within this part of the chapter the connection between material passports and blockchain technology is made. This connection is based on both the literature as on the results from the expert panel.

6.2.1 Connecting aspects with blockchain technology

Not all aspects can be addressed with blockchain technology. For this connection the characteristics of the public permissionless blockchain were used. In the research from Turk and Klinc (2017) about the added value of blockchain technology for construction management almost the same barriers came forward as were seen within the interviews. Since the material passport LLMNT also is based on a BIM model a lot of comparisons can be found and therefore it is useful to compare those barriers. According Turk and Klinc (2017) it is important to note that building information management is the management of information that is used among the different stakeholders throughout the lifecycle of a building. This has similarities with the concept of the material passport.

Redmond, Hore, Alshawi, and West (2012) identified legal and security issues as the main obstacles for using a cloud platform for BIM. Thomas (2013) states that the main obstacles when using a cloud platform for BIM are:

- Who owns the model;
- Who has distribution rights;
- Who has liability for changes or errors;
- How to manage copyright protection;
- How to protect digital intellectual property.

In table 16 is visible which aspects can be addressed with blockchain technology.

Table 16: Aspects material passport related to blockchain technology

Aspects

Clusters	#	Covering code	Supplier	Architect I	Architect II	Advisor	Contractor	Maintainer	Facility manager	Owner	Urban Miner	Recycler	Municipality
Provision of the information	1	Reward system	x	x	x	x				x	x		x
	2	Only necessary information		x			x	x	x		x	x	
	3	Easy handling	x	x					x				
	4	Confidentiality	x	x				x					
	5	Cooperation supply chain				x		x					
	6	Data continuity					x			x			
	7	Standardisation		x			x						
	8	Predevined levels of detail	x										
Storage of the information	1	Ownership data	x	x	x			x		x			x
	2	One data source								x			
	3	Security	x										
Access of the information	1	Predefined who has access	x			x			x	x			
Quality of the information	1	Validation		x	x	x		x	x	x	x	x	
	2	Data management	x			x		x	x	x	x	x	x
	3	Real value					x		x	x	x	x	x
	4	Immutable		x	x	x	x	x					
	5	Traceability									x		
	6	Dynamic during the lifetime		x									
Presentation of the information	1	Uniformity	x		x	x	x	x	x	x		x	x
Process of giving information	1	Added value has to be clear	x			x							
	2	Information request at the beginning	x								x		
	3	Experiment								x			

Provision of the information

Reward system: An important aspect that was mentioned within the interviews was that the companies that provide good information need to be rewarded for their work. With a blockchain a secure value transfer system can be build, in an public permissionless blockchain is this done with a native token (Hileman & Rauchs, 2017). With this token the good behaviour of participants can be rewarded. This can be a financial reward or a reward in the line of a score that represents the good behaviour. With this score good behaviour can be rewarded just like in a tendering process, this is also done within for example EMVI tenders. On the other side can the consequences of reckless behaviour be isolated out to the person who behaved recklessly (Tapscott & Tapscott, 2016).

Data continuity: Within the interviews data continuity was addressed as an important factor for material passports. According to IBM (2017) a key benefit of blockchain technology for supply chain networks is that it establishes a shared, secure record of information flows. It will create a 'shared version of events' across the network for supply chain transactions, processes, and partners. Therefore can blockchain technology stimulate the data continuity when it is implemented within material passports.

Storage of the information

Clear ownership data: Also the ownership of data was seen as important by the interviewees. Especially the part of who owns what data and who is responsible for keeping it up-to-date. With blockchain technology every participant in the network holds a copy of the whole ledger. Therefore, it is always visible for every participant who the owner and responsible is for what data. The transfer of this ownership of the data can also be done in a transparent way and without the help from a thrusted third party (Morabito, 2017).

One data source: According to IBM (2017) a key benefit of blockchain technology for supply chain networks is that it establishes a shared, secure record of information flows. It will create a 'shared version of events' across the networks for supply chain transactions, processes, and partners. Therefore, blockchain will increase record transparency and ease of auditability (Hileman & Rauchs, 2017). If all the information is stored on a blockchain it will get very slow because transferring large data sets is not its strength. But the blockchain can be used as a validation system where can be controlled if a company has the right information. With the blockchain you can create one truth within the network where all the companies can verify if they have the right information.

Access to the information

Predefined who has access: Predefining who has access to the data is seen as an important factor for material passports. Blockchain technology relies on the usage of asymmetric cryptography to sign the digital signatures and encrypt data through the use of private and public key pairs (Kuan Hon, Palfreyman, & Tegart, 2016; Spielman, 2016). With blockchain the information inside the ledger is visible (read access) for all the participants. But rights to adjust the data (write access) is manageable in a good way with the public and private key aspect.

Quality of the information

Validation: Validation of the information is seen as an important aspect for the material passport. If the data lacks quality then no one will use the material passport. Not knowing how to keep the quality up to date in the model was seen as a barrier for material passports. Blockchain technology can provide a useful tool for managing and recording changes in a BIM model throughout its lifecycle. It could store an immutable public record of all the modifications to the model (Turk & Klinc, 2017). When a transaction is verified and approved by the participating nodes of the network, it is almost impossible to adjust this data. This in combination with the aspect of blockchain technology that every participant of the network holds a copy of the whole ledger (Morabito, 2017), implies that there is a form of social control within the system. The consequences of reckless behaviour can be isolated out to the person who behaved recklessly with the use of blockchain technology (Tapscott & Tapscott, 2016). The information that is provided to the model and the changes within the model can always be traced back to the company that was responsible for it.

Data Management: Also the data management is addressed as an opportunity for material passports. Within data management is for example the source of the information important. Blockchain could provide a useful tool for managing and recording changes to a BIM model throughout the different construction phases and the lifecycle of a building. It could store an immutable public record of all the modifications to the model or database (Turk & Klinc, 2017).

Immutable: The data inside the material passport needs to be immutable in order to trust it. The blockchain transparency aspect makes it also a robust network, since it is designed as a distributed network of nodes in which each of these nodes holds a copy of the entire ledger. When a transaction is verified and approved by the participating nodes, it is highly impossible to change or alter the data that is stored. The process of a single rewrite is almost impossible and would require a consensus from the majority (51%) of the members of the entire network (Morabito, 2017). Warranty was also addressed as a barrier that could prevent the usage of used materials. Based on the history of a material can be decided if the material can fulfil the lifecycle of another building. Some interviewees addressed that it is important that this history is immutable.

Traceability: The traceability of materials is mentioned as an important aspect for material passports. In order for the material passport to succeed is it important that the history of materials can be traced back. Blockchain technology can improve the transparency and traceability issues within material passports through the use of an immutable record of data, distributed storage, and controlled user access. A shared, consensus based and immutable ledger helps track the origin and the transformation of the product through the supply chain and the lifecycle of a building (Kshetri, 2017; Pilkington, 2016).

6.2.2 Aspects related to business culture

Within the interviews several aspects came forward that are related to the business culture of companies. These aspects cannot be addressed with blockchain technology. The analysis of these aspects were not directly included inside the scope of this research but it is important to mention those aspects because they can have big influence on how material passports will succeed. Kembro, Näslund, and Olhager (2017) described those aspects related to business culture also in their research. They conducted a Delphi study to explore which factors have influence on the information sharing process across different companies. Business culture regarding sharing information represents the business relationships, attitude, and willingness towards collaborating and sharing information with other companies. These aspects were also mentioned by some of the interviewees. Good inter-firm relationships and trust are seen as critical for enabling the information sharing across different companies. The lack of trust and such relationships, results in a lack of cooperation and non-opportunistic behaviour, appears to be magnified when there are three or more tiers of companies involved (Kembro, Näslund, & Olhager , 2017). The confidentiality issues that were mentioned within the interviews are related to trusting other companies with product related information. The lack of trust within the building sector magnifies the culture where companies want to keep their information inside. Also the home country of a company can for example have influences in how they look towards information sharing. The norms and values of the home country can for example be used as the norms and values for the entire multinational because this gives the company her identity.

6.2.3 Validation relation blockchain with blockchain experts

During the expert meeting with blockchain and circular experts from ABN AMRO the different aspects of material passports were discussed. This expert panel was used to make a substantiated connection between the aspects of material passports and blockchain technology. All the previous described aspects were validated within this meeting with regards to their relation with blockchain technology. It can be concluded that these aspects can be addressed with this new technology. Within the meeting came forward that blockchain technology is useful for addressing the following aspects; reward system, data continuity, ownership data, one data source, predefined who has access, validation, data management, immutability, and traceability. Aside from validating the connection also further opportunities were discussed for the material passport. This concluded in the creation of the improved concept as described in the following paragraph. A summary of this meeting is visible in appendix vi. In the following paragraph an improved situation for material passports will be discussed.

6.2.4 Concept material passport enhanced with blockchain technology

In the previous paragraph was described how the different aspects can be addressed with blockchain technology. In this paragraph an artefact is described how blockchain technology is included in the concept of a material passport. For this enhancement the characteristics of the public permissionless blockchain are used to illustrate the possibilities of this new technology. There is described how this scenario will fulfil the different aspects. This scenario is also be validated by some interviewees to control if it really fulfils the aspects as mentioned within the conducted interviews.

Based on the different aspects that were mentioned during the interviewees a new situation can be created where blockchain technology is included. In this paragraph this situation is described and how it fulfils the different aspects. The situation will be discussed by the six clusters that were also used in the interviews. These six clusters are based on the five format elements as described by Damen (2012). She stated that an information exchange system for material passports need to have the those five format elements is order to succeed. The format elements are: provision, storage, access, quality, and presentation of the information. The structure of providing information for the existing material passport is visible in figure 29. The structure of the material passports that is enhanced with blockchain technology is visible in figure 30.

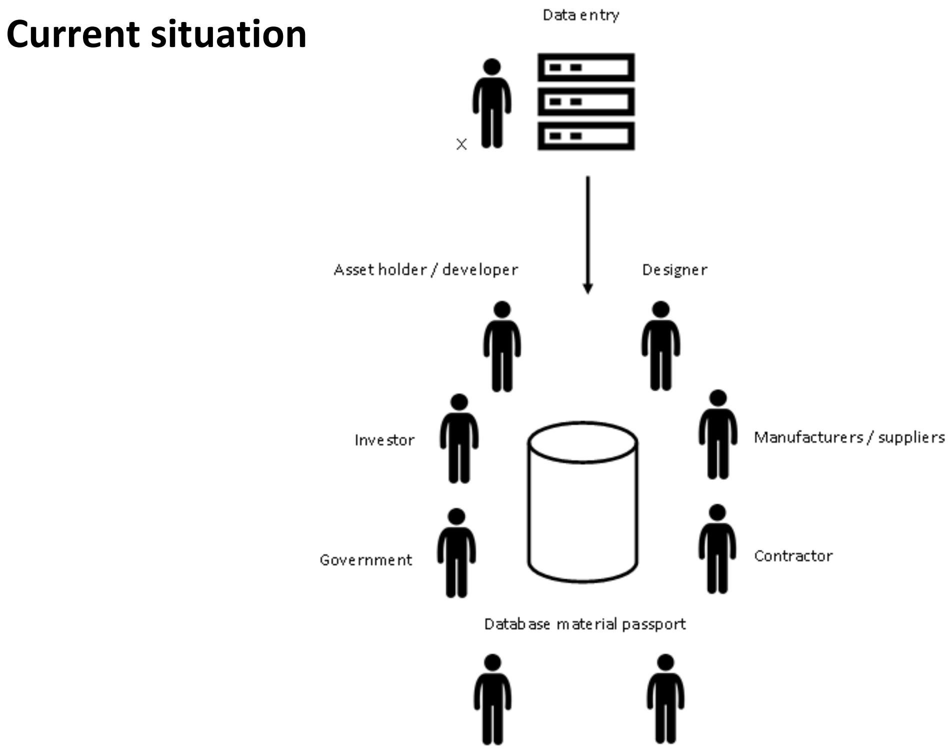


Figure 29: Current situation material passport (own illustration)

Enhanced situation

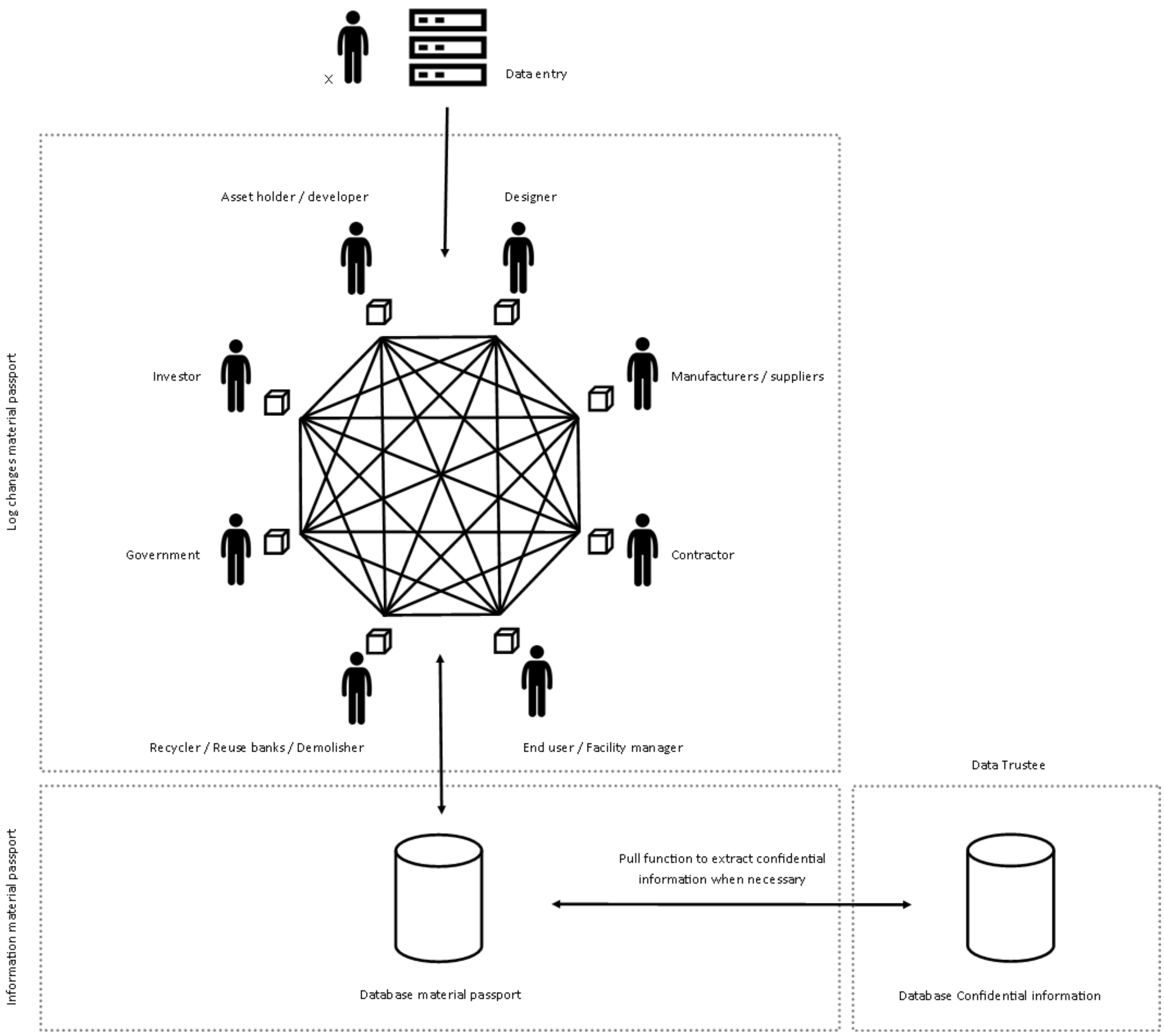


Figure 30: Enhanced situation material passport with blockchain technology (own illustration)

In this new situation the blockchain will be added to the database where the material passports are stored. The LLMNT material passport was used during the interviews as a definition for what a material passport is, this passport is based on the structure of a BIM model. In the improved situation is described how a public permissionless blockchain, as described within the literature review, can improve the concept of material passports. In this improved concept the opportunities about the traceability of materials and information sharing system are included as described within the literature review about blockchain technology.

Provision of the information

Within the new situation everyone is responsible for its own data. The owner of the asset stays responsible for keeping that data up-to-date. As stated by Jain and Benyoucef (2008) the ownership of data is important because someone needs to take responsibility for the data. This was also mentioned within the interviews. Every company is responsible for providing his own information to the material passport, but the owner of the building is the only one with an incentive to keep the whole material passport up to date. All the new information that is provided to the material passport and the adaptions that are made to it will be logged inside the blockchain. Therefore, it is always visible for every participant who the owner and responsible is for what data (Morabito, 2017). Because the blockchain records for every company that is involved what information is given as input it is always traceable who is responsible for what adjustments. This will create a form of social control that will incentivise good input. A requirement that was mentioned within the interviews was that companies that provide good information need to be rewarded for their work. With a blockchain a secure value transfer system can be build, in an public permissionless blockchain this is done with a token (Hileman & Rauchs, 2017). With this token the good behaviour of participants can be rewarded. This can be a financial reward or a reward in the line of a score that represents the good behaviour. This score can be inspired on for example the EMVI score where a certain information provision gives you an advantage. The blockchain is used as a tool for managing and recording changes that are made to the material passport throughout the lifecycle of a building. It stores an immutable public record of all the modifications in the material passport (Turk & Klinc, 2017). Also the transfer of the ownership of data is done in a transparent way with the blockchain (Morabito, 2017).

Storage of the information

In the improved situation the information is still stored inside the database that is owned by owner of the building. The owner of the building is also the only actor in the process that has an incentive to keep the data up to date, as was mentioned within the interviews. In the blockchain only the mutations will be stored. Those mutations will be hashed and stored on the blockchain. With this hash is ensured that the information is not visible for everyone but only for the companies that have also access to it within the material passport. This will create an open character where is visible for each company what adaptions are made inside the passport, but not all the data files will be stored inside the blockchain. When a mutation is verified and approved by the participating nodes, it is highly impossible to change this data which will create a solid dataset that can be used for validation (Morabito, 2017). The information is immutable because it is stored inside the public permissionless blockchain. The blockchain will improve the material passport on traceability, immutability, and warranty aspects, as were mentioned by the interviewees.

Access to the information

The access within the material passport will be structured according to who has what rights. Within the blockchain only the adjustments to the data in the material passport are stored and visible, this will result in that the specific data is only visible to the company that has also rights to it inside the database. Within the blockchain will be visible that a company has made an adjustment. But only the companies that have access to the data inside the database can control what the specific adjustment is. Blockchain technology relies on the usage cryptography to sign and encrypt data through the use of private and public key pairs (Kuan Hon, Palfreyman, & Tegart, 2016; Spielman, 2016). With this aspect of blockchain technology the write access for data can be managed in a good way, it is always clear who is responsible for what adjustments. Kembro, et al. (2017) mention that especially when information is shared with a multitude of companies, that it is dificult to control exactly what information is shared with whom. With the use of blockchain technology for material passports there is always one location which state what information is sent with whom. This information is hashed and therefore only readably by the companies that have also acces to it inside the material passport, with this also the read access can be managed in a good way.

Another important aspect that was mentioned within the interviews were confidentiality aspects of the information that is stored. This barrier was also mentioned in other researches like the research Debacker and Manshoven (2016), Damen (2012), and the research of Lee and Wang (2000). Blockchain cannot address this aspect because of its transparent nature. Bechini, et al. (2008) suggest that in order to guarantee the confidentiality aspect, data can be stored on in-house-servers and others are only provided with the tracability of information. This situation requires a data trustee inside the process of information sharing. With this data-trustee the information that is confidential can be stored with a pull meganism towards the material passport. The date-trustee acsts like an escrow agent, it holds the actors data untill a legitimate need arises. Bechini, et al. (2008) also suggest to use multiple data-trustees so the companies can choose who they trust their data to. A possible company that can fill in the place of the data trustee is the bank that is also responsible for financing the specific asset.

Quality of the information

The information quality is an important aspect for material passports and refers to the accuracy, timelines, adequacy, credibility of the information that is exchanged. Jain and Benyoucef (2008) described that businesses are becoming more web-based wich will result in improved quality of the information. The creation of material passports can also be placed inside this trend. Within the interviews about the material passport was the quality of the information also mentioned as an important aspect. Not knowing how the quality of the information can be validated is seen as a barrier. Adding a blockchain on top of the database where material passport are stored is enhancing the structure of the data management system by managing and recording changes to the material passport. The blockchain will store an immutable public record of all the modifications in the material passport (Turk & Klinc, 2017). With the blockchain you can create one truth in the network where all the companies can verify if they have the right information. When a transaction is verified and approved by the participating nodes, it is highly impossible to change the data. This in combination with the aspect of blockchain technology that every participant of the network holds a copy of the whole ledger (Morabito, 2017), implies that there is a form of social control within the system. The consequences of reckless behaviour are isolated out to the person who behaved recklessly (Tapscott & Tapscott, 2016). With this structure can always be traced back what company is responsible for what data and the adjustments within the material passport. The public permissionless blockchain will also ensure that when the data needs to be transferred from one material passport to another material passport that data manipulation can be prevented. This is ensured because the different material passports will use the same blockchain as validation. Because the evolution of the data is stored inside the blockchain, there can always be controlled if normal wood for example will not get the FSC quality mark when it is transferred between different material passports.

Presentation of the information

Lambert (2001) states that unification of the method of description is indispensable since there is a need to understand the information at every stage of the supply chain and the lifecycle of a building. Unification enables integrated decision making and allow the different actors during the lifecycle of a building to quickly evaluate the available information. Because there is no centralized planner within the supply chain and the decision making occurs in a decentralized way, it is important that the information is presented in a unified but decentralized model (Sahin & Robinson, 2002). Within the interviews is stated that the implementation of the material passports will stimulate the uniformity within the market. But the addition of blockchain within material passports will not stimulate this in an extra way.

Process of giving information

Within the interviews was stated that the implementation of the material passports will stimulate the whole process of information sharing across the lifecycle of a building. But the information request has to be done in the beginning of the project. Also it has to be clear for the different parties what the added value is. For this, a shared vision needs to be created on how the material passport fills the information gap. As stated by Damen (2012) the usage of a material passport can stimulate this shared vision, but the addition of blockchain technology within material passports will not stimulate this in an extra way.

6.2.5 Disadvantages enhancement with blockchain technology

The open structure of a blockchain is not preferable for all the information that is stored inside the material passport. For this reason was chosen to not store all the information within the blockchain. Also could the blockchain not handle the large BIM models from the material passport as was discussed within the expert meeting. The open structure of a blockchain could stand opposite towards the aspect that came from the interviews about the confidentiality and security of the information that is stored within the passport. Mtethwa (2016) also addressed security and privacy as a limitation of blockchain technology. Therefore only the adaptions within the material passport are stored. The specific information about the materials are still stored inside the database of the material passport.

6.3 Conclusion and discussion blockchain enhancement

Not all aspects that were mentioned during the interviews can be addressed with blockchain technology. With an expert panel on blockchain technology and circular economy was analysed which aspects can be addressed. Based on these aspects an improved situation was designed. This new situation was designed with the characteristics of the public permissionless blockchain.

In the improved situation the information is still stored inside a database that is owned by the owner of the asset, the owner of the asset stays responsible for keeping the data up to date. Every company is responsible for providing his own information to the material passport, but the owner is the only company with the incentive to keep the whole material passport up-to-date. All the new information that will be provided to the material passport will be logged inside the blockchain. Also the adaptions in the material passport are logged inside this blockchain. The access within the material passport will be structured according who has what rights. A requirement that was mentioned during the interviews was that the companies that provide good information need to be rewarded for their work. This can be a financial reward or a reward based on reputation. This is created in the new situation with a native token.

With the blockchain you can create one truth in the network where all the companies can verify if they have the right information. When a transaction is verified and approved by the participating nodes, it is highly impossible to change or alter the data. This in combination with the aspect of blockchain technology that every participant of the network holds a copy of the ledger implies that there is some sort of social control within the system. This will incentivise the input of good information. Blockchain will be used as a tool for managing and recording changes to the material passport throughout its lifecycle. The adjustments within material passports are always traceable back to the person that was responsible for it. Also the transfer of the ownership of data can be done in a transparent way with the blockchain. Within the interviews was also stated that the implementation of the material passports will stimulate the uniformity within the market. But the addition of blockchain within material passports will not stimulate this extra.

The addition of blockchain technology has not only positive sides for the material passport. On the aspect of security and confidentiality the core aspects of blockchain technology are in line with some aspects that were mentioned during the interviews. Therefore was chosen to only store the mutations in the blockchain. With this solution the core aspects of blockchain can be used to improve the material passport but not all the specific information is stored and visible for every participant in the network.

It is important to recognise that the proposed situation within this chapter is based on the actors of the case of the CIRCL pavilion extended with four other interviews. Besides this is the solution based on the material passport LLMNT from the CIRCL pavilion. The proposed improvement can therefore not be generalised to other material passports because it is possible that those passports are structured in a different way. The idea behind this solution can be used to create an improvement for another material passport. But it cannot be used as a 1:1 fit on another material passports or cases.

7. Empirical research: Validation enhanced material passport

Within the previous chapter the validation of blockchain technology was discussed. Also the improved concept of the material passport enhanced with blockchain technology is presented. This improved concept was made in cooperation with experts from ABN AMRO. To validate if this improved concept has really an added value a validation with some of the interviewees is conducted. In this chapter the outcomes from this validation are discussed.

7.1 Research description

To validate if the enhanced material passport has really an added value some validation interviews were conducted. The optimized situation was reviewed again by certain interviewees. In this validation the interviewees were asked whether the new concept will fulfil the different aspects of the material passport. The output from these validation interviews were used to improve the enhanced material passport. In table 17 is visible which actors are included in the validation.

Table 17: Validation

#	Company	Role
1	Supplier	R&D Mechanical Engineer
2	Architect	Associate
3	Contractor	Director Sustainability
4	Owner	Advisor Circular Economy

7.2 Empirical findings validation enhanced material passport

The improved situation was validated with four of the interviewees to control if it adds value. For the validation the supplier, architect, contractor, and owner were interviewed again.

Supplier

Within the validation with the supplier came forward that the system fails or stands with the reward system. When you can reward the company that provides information, this will stimulate the provision of good information. This will result in the improved quality of the data that is stored in the material passport. Therefore they see an added value of blockchain technology for the material passport. Also that the materials can be traced in a better way when the mutations are logged inside the blockchain is seen as a good improvement. This will create one source of information that is leading.

Architect

Within the validation with the architect was acknowledged that the definition of the material passport was done in a proper way. Also keeping the ownership of the material passport with the owner of the asset was seen as important. The addition of blockchain technology on top of the material passport as a form of validation is seen as an added value. They see the social control within the system as a good improvement. The material passport succeed or fails based on the data that is stored in it. The additional solution to work with the data trustee is also seen as important. It makes the material passport more difficult if you look to the structure, but there is also recognised that it is inevitably. This structure with the data trustee needs to be investigated more.

Contractor

Within the validation with the contractor was validated that they see the improvement of blockchain technology added to the material passport as useful. Without the validation, the material passport runs the risk of getting out of date and becoming static. When the information is validated, the material passport becomes a good depository of correct data. The social control will stimulate good information. Also the tracking of the materials is seen as important. In the blockchain is always traceable what has happened with the materials during their life. In this way, blockchain technology is helpful to improve the concept of material passports.

Owner

Within the validation with the owner the added value of the improved transparency and trust within system was seen as important. The blockchain added to the material passport was seen as an improvement for the validation of the information. The creation of the social control within the material passport is also seen as an improvement. Within the validation came also forward that this social control is possible less important for projects from the government because they are already seen as a thrusted party within the market. But for the improvement of the quality of the data it is still important. Especially regarding the teams that currently control all the data on their correctness, this improvement could make their work more efficient.

7.3 Conclusion and discussion enhanced material passport

Within the validation of the improved situation was validated if the situation really adds value compared to the current situation. The improved situation was validated with some of the interviewees. Due to the time limit of this research it was not possible to validate the improved situation with all of the interviewees. The different interviewees stated that they see an added value when blockchain technology is implemented in material passports. From this can be concluded that in the scope of this research the enhancement of blockchain is useful for material passports. The outcomes of this validation cannot be generalized across other cases because of the explorative nature of this research. Although, the outcomes can be used to inspire the innovation of other material passports with blockchain technology.

8. Conclusion, discussion, and further research

Despite widespread interest in blockchain technology and material passports, the literature on blockchain in relation to material passports is limited. This research contributes to this field by identifying aspects that are vital for the implementation of material passports. Experts have decided how these aspects can be addressed with blockchain technology. This work has resulted in an improved approach to using blockchain technology to improve material passports.

8.1 Conclusion

The conclusion answers the main research question (MQ). To answer the main-question, the sub-questions (SQs) are addressed. At the start of this research, nine sub-questions were formulated and they provide the basis for answering the main research question. Therefore all the sub-questions are addressed in this chapter. First the sub-questions are answered and then the answer to the main question is given. The main research question was as follows:

> *To what extent can blockchain technology be used to improve the implementation of material passports in the circular built environment?*

SQ1: What is a circular economy?

The concept of a circular economy has its origin in various schools of thought. It redesigns the economic system by focusing on closing the material flows and being regenerative by intention and design. The system is focused on keeping the value of products as high as possible and waste is minimized. The Ellen MacArthur Foundation (2013b) described five principles that underpin a circular economy: design out waste, build resilience through diversity, rely on energy from renewable sources, think in systems, and waste is food. Based on these principles, different ways of closing the loop are created that keep the value of materials as high as possible. The biological cycles are based on non-toxic materials that can be restored back into the biosphere. The loops for the technological cycle are about keeping products at their highest value and consist of; lengthening the lifecycle, reuse or redistribute, refurbish or remanufacture, and recycle.

SQ2: What does a circular economy mean for the built environment?

In transitioning to a circular economy, cities will play a profound role as increasing urbanisation is expected in the coming years. Cities have a high concentration of resources, capital, data, and talent within a small territory, which places them uniquely for this transition. Circular cities aim to eliminate waste, to keep assets always at their highest value, and to enable digital technology. The building sector is unique compared to other sectors that are transitioning to a circular economy. This is not only due to the complexity of buildings but also relates to other factors, such as the long lifespan of a building. Inside the built environment different initiatives regarding a circular economy are based on the idea of buildings as material banks, this view radically changes how material flows need to be managed. It ensures that materials and products can be reused many times without significant adjustments.

SQ3: What is a material passport, and what kind of information is stored in these passports?

The lack of information is often mentioned as a barrier that prevents implementation of a circular economy. Material passports are created to provide a solution to the barrier of missing information. Passports are an active tool for value tracking and are aimed at gaining insight into the real value of materials. A material passport describes all the materials, components, and elements that are used inside a building. These materials can be allocated for reuse, resale, and recycling. The material passport gives materials their identity and value. To understand the circular value potential of products, systems, and materials, reliable information is required. Actions at every stage of the lifecycle of a building, from production to use, maintenance, and demolition have an impact on products and systems, as well as their value recovery potential. A material passport makes this information available and relevant at each stage.

SQ4: What is blockchain technology and how does it work?
A blockchain is essentially a distributed database that contains all the records of all digital events that ever have been executed and shared among the participating parties. Each record in the public ledger is verified by consensus of the majority of participants in the network. Every node in the network holds a full copy of these events and the copies are constantly updated. This process creates one truth within the network, through a shared immutable database that is distributed to all participants.

Research shows that blockchain technology is still at an early stage of development and therefore needs to overcome certain limitations and challenges. These challenges include awareness and understanding, security and privacy, regulations and governance, scalability, and computing power. To improve widespread, adoption technical standards must be developed and accepted across different industries.

SQ5: What opportunities exist for blockchain technology to improve material passports?
Within the literature review, three opportunities were analysed for how blockchain technology could improve material passports. These opportunities were identified by verifying the theoretical blockchain solutions. The opportunities were then used to identify possible improvements for material passports. The following opportunities were identified:

- Digital records of real estate assets;
- Traceability of materials;
- Information sharing system.

The sub questions six and seven both were used as input to get a comprehensive list of aspects for the material passport. Therefore are these sub questions combined within this conclusion.
SQ6: What are the barriers to sharing information from material passports? / SQ7: What are the requirements for data that are taken from a material passport before this data can be used by the different users?
In the interviews, people focussed on finding the barriers that are felt in the market with regard to using material passports. These barriers could prevent the successful implementation of material passports. Besides focusing on the barriers, participants also a focused on identifying the requirements for material passports. These requirements help in analysing which aspects must be included in the system in which material passports are stored. These factors can ensure that companies trust the system. However, what is experienced as a barrier by one interviewee can be described as a requirement by another. Therefore, a comprehensive list was made of the different aspects for material passports. There was also analysed which aspects could be addressed with blockchain technology.

SQ8: How can blockchain technology remove the barriers or fulfil the requirements?
Not all aspects that were mentioned during the interviews can be addressed with blockchain technology. An expert panel determined which aspects can be addressed by the public permissionless blockchain. Within this enhanced situation, a blockchain layer would be added to the database where the material passports are stored. The public permissionless blockchain was used in this research, as this type of blockchain illustrates the possibilities of the new technology.

SQ9: Who are the most important actors in relation to the implementation of material passports?
Within the interviews there was also a focus on finding the most important actors in relation to the implementation of material passports. The owner of the building and the government were cited as the most important actors. The owner is important because he owns the asset and therefore has an

incentive to keep the data in good form and up-to-date. The government was also mentioned often in relation to regulations. The bank was mentioned as important. If banks require material passports for financing, the market will immediately experience an financial incentive to use the passports.

Based on these sub-questions, the main-question of this thesis can be answered.

MQ: To what extent can blockchain technology be used to improve the concept of material passports in the circular built environment?

This research practically and theoretically contributes to the field of blockchain technology in relation to material passports. Based on the various aspects that were mentioned by interviewees, a new scenario was envisaged in which blockchain technology was included for material passports. Within this situation, blockchain technology is added to the database in which material passports are stored. The public permissionless blockchain is used for validating all the data entries and adjustments within the material passport. This process creates one truth within the network that is accessible by all participants. Within this blockchain, it is always visible who the owner is and who has made what adjustments to the data. The open and immutable aspect of the blockchain incentivises the input of good information by creating a form of social control. Good behaviour can also be rewarded with a native token that exists within the network, this can be a financial reward or a reward based on reputation. It is always possible to trace the history is of a material. Because adjustments alone are stored in the blockchain, the storage of excessive data is prevented. Confidentiality is not hampered by this structure. The enhanced scenario is discussed with regard to data provision, storage, access, quality, and presentation, and the process of giving information.

8.2 Discussion

This research was conducted in cooperation with ABN AMRO, with the objective of investigating the blockchain potential for material passports within a circular economy. The findings of this study are based on in-depth qualitative research using individual semi-structured interviews. To increase the research validity, triangulation of information was conducted. The material passports were identified through desk research and validated in the interviews. Also, opportunities for blockchain technology in material passports were identified through desk research and validated by an expert panel. This increases the internal validity of the results. The external validity of this explorative research is low. However, since the research was explorative, the results are not meant to be generalized to other cases.

Due to the novelty of blockchain technology and material passports, both concepts are currently still quite immature. All the data used in this research were empirical data and described the perceived effects. During the interviews about material passports, the expected barriers and requirements were discussed. There was decided to leave the connection with blockchain technology out of the interviews because this would have made the interviews too complex. The enhancement of blockchain technology on material passports were therefore explored with the help of an expert panel instead, drawn from ABN AMRO. Therefore, the results of this research show the perceived consequences rather than real consequences based on a long track record of experience with material passports. To validate the assumptions that were made by the expert panel, another validation was implemented with certain interviewees. The concept of an improved material passport that uses blockchain technology was validated by validation interviews to determine if it offers added value. This step increased the validity of the research, but the assumptions that were made could not be tested quantitatively in the absence of more pilot projects or further data on this topic.

The novelty of the concept of material passports had the consequence that the answers given in the interviews tended to be rather abstract. The respondents talked about perceived barriers and requirements. This resulted in the answers being more superficial than was expected, mainly because respondents did not have a strong track record in working with material passports.

Within the material passport LLMNT also a lot changed during the time in which this research was conducted. Appendix v shows what the original set up of LLMNT was, and what the final version is that is released. The comparison illustrates that the original set-up was very specific, in this proposed version, substantial information was asked from the different stakeholders. The interviews highlighted that it is important to only ask the necessary information. Appendix v also shows that the final version of the passport is much more compact. For a wide implementation, if the request for information appears to complex, respondents will not provide all the requested information. It is thus important to determine what information is necessary for the various stakeholders to be included in the material passport. The lack of such knowledge was mentioned within the interviews.

Since blockchain technology is still in an immature phase, many of the expected benefits provided by the technology are exaggerated in terms of impact by the parties who benefit from implementing the technology. Therefore, a vast 'hype' about blockchain technology is created, which leads to misunderstandings and misconceptions of the real benefits and the real use. This hype was confirmed by Gartner, which identifies blockchain just over the top of the hype cycle in 2017 (Gartner, 2017). Blockchain is often seen as a panacea for all kinds of problems. This research offers with substantiated reasoning a clear and realistic picture of how blockchain can address some aspects of material passports. However, the benefits that are proposed must be weighed against the costs of blockchain implementation, to evaluate the real advantage provided by this new technology.

Bias within the outcomes was tried to be lowered as much as possible in the research process, methodology, and argumentation of the results. First, the framework of Hevner, March, and Park (2004) was used to accommodate the exploratory nature of this study, and provided a basis for developing a research framework for this study. Second, the interview protocol was based on the guidelines by Baarda, Goede, and Teunissen (2005), and the case with the interviews were selected in order to collect in depth information about material passports. Third, weekly in-depth sessions were conducted with the company supervisor, Alexa Krayenhoff, and intermittently with the university supervisors, Qi Han and Marleen Hermans. Last, in this research, there was tried to stay as close to the empirical findings as possible to reduce the risk of that subjective ideas and interpretations became more influential than the empirical data. To ensure this, different validations were implemented in this research. This research therefore provides a solid basis on which further research can be built.

8.3 Further research

This thesis is the first academic study of connecting blockchain technology to material passports. It has an exploratory nature and is focused solely on identifying the possible opportunities in how blockchain technology can enhance material passports. Therefore, much was not explained by this study. Despite the extensive theoretical framework, interviews, expert session, and validations, this study might raise many regarding the proposed solution. Therefore, various directions for further research can be identified.

Blockchain technology

The first opportunity for future research relates to the scoping of this research. To provide a clear scope for this research, the characteristics of the public permissionless blockchain were selected to investigate what opportunities exist. This scoping was chosen because the open permissionless blockchain illustrates the possibilities of the new technology. Currently, on almost a daily basis new concepts are proposed for how blockchain technology with certain permission models can address actual business problems. Therefore, the first recommendation is to broaden the blockchain scope to investigate which other types of blockchain could be attractive for improving material passports.

Distributed ledger technology could also be studied as it might create even more for enhancement the information sharing of data and automating the rights and obligations of the network. In addition to blockchain, other types of databases could be investigated to compare them to blockchain technology.

Material passports

Within the field of material passports, academic research is still in its infancy. For this reason, the material passport LLMNT was used in this study to provide a definition for material passports. Further research can investigate whether using other material passports would result in the same barriers or requirements. The lack of a standard was seen by different companies as a barrier to implementation. Therefore, further research could focus on creating a standard for material passports, based on scientific literature. Another avenue for further research on material passports is related to the existing building supply. All material passports that are currently developed are focused on implementation within new buildings, for example using BIM models. The biggest challenge lies in how material passports can be made usable for the current building supply where not all information is directly available.

Interview population

Because of the timeframe of this thesis, there was chosen to interview one actor from every role that uses material passports. Therefore this study was based on N=1 of every actor included in the lifecycle of a building, which resulted in low external validity. To improve the external validity, more persons in every role could be interviewed to ensure that all aspects are covered. A stronger focus could be placed on the asset holders, because their role has the incentive and mandate to implement material passports.

Marketplace

When material passports are implemented within marketplaces to sell or buy used materials, the added value of blockchain can be even higher. The characteristic ability of blockchain to transfer value can be used to build a sort of marketplace where materials can be sold. The connection with material passports here is an interesting viewpoint, because the history of materials is then included in the transaction. Therefore, a possible direction for further research is to explore how blockchain can be used to stimulate the transfer of materials and assets between different owners.

Internet of things and smart contracts

When the internet of things with pay-per-use structures is implemented within material passports, many other options will arise where blockchain technology could play a useful role. For example, smart contracts could manage the whole pay-per-use process. This is an interesting concept that could be explored further.

8.4 Practical recommendations

The adoption of material passports and blockchain technology among participants in the Dutch real estate sector is still in its infancy. This study provided insight into possibilities for implementing blockchain technology in material passports. The results highlighted aspects of material passports that could be improved, and several recommendations for business implementation are formulated below.

Standardisation material passports

According to the interviewees, currently different initiatives regarding material passports are being created in many places. All these initiatives have their own focus, which results in a lack of definition for material passports. Interviewees stated that they see the potential for material passports but that the lack of a standard holds them back from supporting diverse initiatives. This scenario can also be related to improvement in blockchain technology. A material passport is only as good as the data that are stored in it, so standardisation in material passports is essential to improve the data exchange between different passports when materials are exchanged. Blockchain technology can facilitate this transfer.

Governmental regulation

The coordination of implementing material passports remains slow. The results showed that market players view the government as the main actor to take the first step. This could be a case of setting a good example but should also oblige companies to use material passports, as that would create an incentive for asset owners to implement the passports. Because of the lack of incentive for material passports, implementation currently also does not happen widely. Asset owners gain no return on their investment until a building is disassembled. The obligation from the government would create the first incentive for implementing material passports, which in turn would stimulate the creation of new business models based on these passports, which would support the use of such passports. The new business models might also ensure that the investment would be earned back quickly.

Collaboration

To achieve widespread adoption, technical standards must be produced and agreed on across the industry. Currently people are experimenting with the implementation of blockchain technology and material passports. However, each project has its own focus and rules. Hence, it is possible that all stakeholders might develop their own environments without those environments being able to communicate which each other. Such a scenario contradicts the idea behind both material passports and blockchain technology. All stakeholders need to cooperate on a wider scale to create a uniform framework for the transfer of assets and materials.

Bibliography

Abeyratne, S., & Monfared, R. (2016). Blockchain ready manufacturing supply chain using distributed ledger. *International Journal of Research in Engineering and Technology 5*, 1-10.

Accenture. (2014). *Circular Advantage: Innovative Business Models and Technologies to Create Value in a World without Limits to Growth.* Accenture.

Andrews, D. (2015). The circular economy, design thinking and education for sustainability. *Local Economy 30*, 305 - 315.

Atzori, M. (2015). *Blockchain Technology and Decentralized Governance: Is the State Still Necessary?* University of Nicosia.

Baarda, D., & Goede, M. d. (2006). *Basisboek Methoden en Technieken .* Houten: Noordhoff Uitgevers.

Baarda, D., Goede, M. d., & Teunissen, J. (2005). *Basisboek kwalitatief onderzoek.* Houten: Noordhoff Uitgevers.

Bastein, T., & Rietveld, E. (2015). *Materialen in de Nederlandse economie - Een kwetsbaarheidsanalyse.* Delft: TNO.

Bastein, T., Roelofs, E., Rietveld, E., & Hoogendoorn, A. (2013). *Kansen voor de circulaire economie in Nederland.* Delft: TNO.

Bauman, D., Lindblom, P., & Olsson, C. (2016). *Blockchain Decetralized Trust.* Stockholm: Entreprenörskaps Forum.

Bechini, A., Cimino, M., Marcelloni, F., & Tomasi, A. (2008). Patterns and technologies for enabling supply chain traceability through collaborative e-business. *Information and Software Technology 50*, 342–359.

Benyus, J. (1998). *Biomimicry: Innovation inspired by nature.* New York: Harper Perennial.

Beurskens, P., & Bakx, R. (2015). *Built-to-rebuild The development of a framework for buildings according to the circular economy concept, which will be specifed for the design of circular facades.* Eindhoven: Eindhoven University of Technology.

Boer, Y. d., & Bergen, B. v. (2012). *Expect the Unexpected: Building business value in a changing world.* KPMG International.

Bokeloh, P., Krayenhoff, A., Menkveld, N., Raes, J., & Schotsman, H. (2017). *Prinsjesdagrapport 2017, De Cirkel is rond: De circulaire toekomst van Nederland.* Amsterdam: ABN AMRO.

Brand, S. (1994). *How Buildings Learn: What happens after they're built.* Penguin Publishing.

Brenig, C., Schwarz , J., & Rückeshäuser , N. (2016). Value of Decentralized Consensus Systems - Evaluation Framework. *Research Papers. 75*, 1 - 18.

Brill, J., Cuomo, J., Gopinath, R., Korsten, P., McDermott, B., McLean, J., . . . Wallis, J. (2016). *Fast forward Rethinking enterprises, ecosystems and economies with blockchains.* New York: IBM Institute for Business Value.

Brundtland Commission, United Nations. (1987). *Report of the World Commission on Environment and Development: Our Common Future.* United Nations.

Carra, G., & Magdani, N. (2017). *Circular Business Models for the Built Environment.* Ellen MacArthur Foundation, ARUP, BAM.

Circle Economy. (2015). *Circular Amsterdam A vision and action agenda for the city and metropolitan area.* Amsterdam: Circle Economy, TNO and Fabric.

Cooper, M., Ellram, L., Gardner, J., & Hanks, A. (1997). Meshing Multiple Alliances. *Journall of Business Logistics 18*, 67 - 89.

Cremer, A., & Taylor, E. (2016, 4 22). *Volkswagen takes $18 billion hit over emissions scandal*. Retrieved from Reuters: https://www.reuters.com/article/us-volkswagen-emissions-germany-probe/volkswagen-takes-18-billion-hit-over-emissions-scandal-idUSKCN0XJ19U

Crosby, M., Nachiappan, Pattanayak, P., Verma, S., & Kalyanaraman, V. (2016). Blockchain Technology: Beyond Bitcoin. *Applied Innovation Review 2*, 6-19.

Damen, M. A. (2012). *A resource passport for a circular economy.* Utrecht: University Utrecht.

de Architekten Cie. (2017, 11 1). *Circl - ABN AMRO paviljoen*. Retrieved from de Architekten Cie: http://www.cie.nl/projects/174#

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

Debacker, W., & Manshoven, S. (2016). *D1 Synthesis of the state-of-the-art Key barriers and opportunities for Materials Passports and Reversible Building Design in the current system.* BAMB.

Dijkstra, M. (2017). *Blockchain: Towards disruption in the real estate sector.* Delft: Delft University of Technology.

Dobbs, R., Oppenheim, J., Thompson, F., Brinkman, M., & Zornes, M. (2011). *Resource Revolution: Meeting the world's energy, materials, food, and water needs.* Mckinsey & Company.

Dorri, A., Kanhere, S., & Jurdak, R. (2017). Towards an Optimized BlockChain for IoT. *Proceedings of the 2nd ACM/IEEE International Conference on Internet-of-Things Design and Implementation*, 173-178.

Drescher, D. (2017). *Blockchain Basics: A Non-Technical Introduction in 25 Steps.* New York: Apress.

Durmisevic, E., & Brouwer, J. (2006). *Design Aspects of Decomposable Building Structures.* Delft: Delft University of Technology.

Dutch Blockchain Coalition. (2017). *Actieagenda Nationale Blockchain Coalitie.* Dutch Blockchain Coalition.

Ellen MacArthur Foundation. (2013a). *Towards the Circular Economy, Oppertunities for the consumer goods sector.* Ellen MacArthur Foundation.

Ellen MacArthur Foundation. (2013b). *Towards the Circular Economy: Economic and business rationale for an accelerated transition.* Ellen MacArthur Foundation.

Ellen MacArthur Foundation. (2014). *Towards the Circular Economy: Acceleration the scale-up across global supply chains.* Ellen MacArthur Foundation.

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

Ellen Macarthur Foundation. (2017a). *Cities in the Circular Economy: An Initial Exploration.* Ellen Macarthur Foundation.

Ellen MacArthur Foundation. (2017b). *Intelligent Assets: Unlocking the Circular Economy potential.* Ellen MacArthur Foundation.

Ellen MacArthur Foundation. (n.d.). *Schools Of Thought*. Retrieved from Ellen MacArthur Foundation: https://www.ellenmacarthurfoundation.org/circular-economy/schools-of-thought

Ethereum. (2017, 10 10). *Ethereum*. Retrieved from Ethereum.org: https://ethereum.org/

European Commission. (2014a). *Towards a circular economy: A zero waste programme for Europe.* Brussels: European Commission.

Francisconi, M. (2017). *An explorative study on blockchain technology in application to port logistics.* Delft: Delft University of Technology.

Frøystad, P., & Holm, J. (2015). *Blockchain: Powering the Internet of Value.* Evry.

Gartner. (2017, 8 15). *Top Trends in the Gartner Hype Cycle for Emerging Technologies, 2017*. Retrieved from Gartner: https://www.gartner.com/smarterwithgartner/top-trends-in-the-gartner-hype-cycle-for-emerging-technologies-2017/

Geldermans, R. (2016). Design for change and circularity – accommodating circular material & product flows in construction. *Energy Procedia 96*, 301 – 311.

Google. (2017, 6 14). *Google trends*. Retrieved from Google: https://trends.google.nl/trends/explore?q=blockchain

Hevner, A., March, S., & Park, J. (2004). Design Science in Information Systems Research. *MIS Quarterly 28*, 75-105.

Hileman, G., & Rauchs, M. (2017). *Global Blockchain Benchmark Study.* Cambridge: University of Cambridge.

IBM. (2017). *The Benefits of Blockchain to Supply Chain Networks.* IBM.

Idelberger, F., Governatori, G., Riveret, R., & Sartor, G. (2016). Evaluation of logic-based smart contracts for blockchain systems. *International Symposium on Rules and Rule Markup Languages for the Semantic Web*, 167-183.

Jain, V., & Benyoucef, L. (2008). Managing long supply chain networks: some emerging issues and challenges. *Journal of Manufacturing Technology Management 19*, 469 – 496.

Joustra, D., de Jong, E., & Engelaer, F. (2013). *Guided Choices Towards a Circular Business Model.* Cradle to Cradle in Business Sites.

Kembro, J., Näslund, D., & Olhager , J. (2017). Information sharing across multiple supply chain tiers: A Delphi study on antecedents. *International Journal of Production Economics 193*, 77–86.

Khasreen, M., Banfill, P., & Menzies, G. (2009). Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. *Sustainability 1*, 674-701.

Kim, H., & Laskowski, M. (2016). Towards an Ontology-Driven Blockchain Design for Supply Chain Provenance.

Kok, L., Wurpel, G., & Ten Wolde, A. (2013). *Unleashing the Power of the Circular Economy.* Amsterdam: Report by IMSA Amsterdam for Circle Economy.

Kovacic, I., Honic, M., & Rechberger, H. (2017). *BIM Based Material Building Pass as Tool for Enhancement of Circular Economy in AEC Industry.* Vienna: Vienna University of Technology.

Kshetri, N. (2017). Blockchain's roles in strengthening cybersecurity and protecting privacy. *Telecommunications Policy*, 1–12.

Kuan Hon, W., Palfreyman, J., & Tegart, M. (2016). *Distributed Ledger Technology & Cybersecurity, Improving information security in the financial sector.* Heraklion: European Union Agency For Network And Information Security.

Kubbinga, B., Fischer, A., Achterberg, E., Ramkumar, S., de Wit, M., van Heel, P., . . . Brekelmans, H. (2017). *Toekomstbestendig Vastgoed Bouwen: Aan de slag met circulaire verdienmodellen.* Amsterdam: Circle Economy, ABN Amro.

Kumar, R. (2011). *Research Methodology - a step-by-step guide for beginners.* London: SAGE.

Lambert, A. (2001). Life-cycle analysis including recycling. In J. Sarkis, *Greener manufacturing and operations : from design to delivery and back* (pp. 36-55). Sheffield: Greenleaf.

Lee, H., & Wang, S. (1998). Information Sharing in a Supply Chain. *Stanford University, Research Paper No. 1549*.

Lee, H., & Wang, S. (2000). Information sharing in a supply chain. *Journal of Technology Management 20*, 373–387.

Leising, E. (2016). *Circular Supply Chain Collaboration In the Built Environment.* Delft: Delft University of Technology.

Li, S., & Lin, B. (2006). Accessing information sharing and information quality in supply chain management. *Decision Support Systems 42*, 1641–1656.

Lotfi, Z., Mukhtar, M., Sahran, S., & Taei Zadeh, A. (2013). Information Sharing in Supply Chain Management. *Procedia Technology 11*, 298 - 304.

Luscuere, L. (2017). Materials Passports: Optimising value recovery from materials. *Waste and Resource Management 170*, 25 - 28.

Lyle, J. (1994). *Regenerative Design for Sustainible Development.* New York: John Wiley & Sons Inc.

McDonough, W., & Braungart, M. (2002). *Cradle to Cradle.* New York: North Point Press.

Meadows, D., Meadows, D., Randers, J., & Behrens Ill, W. (1972). *The Limits to Growth.* New York: Universe Books.

Ministry of Economic Affairs. (2016). *Nederland circulair in 2050: Rijksbreed programma circulaire economie.* Den Haag: Ministry of Economic Affairs.

Morabito, V. (2017). *Business Innovation Through Blockchain: The B³ Perspective.* Cham: Springer.

Mougayar, W. (2016). *The Business Blockchain, Promise, Practice, and Application of the Next Internet Technology.* Hoboken: John Wiley & Sons Inc.

Mthethwa, S. (2016). The Analysis of the Blockchain Technology and Challenges Hampering Its Adoption. *International Science Index, Computer and Information Engineering 3*, 143-150.

Nagel, J., & Korbee, P. (2017, 10 5). *Assetmanagement.* Retrieved from Platoform WOW (Rijkswaterstaat): https://www.platformwow.nl/verslagen/presentaties-en-terugblikken-workshops-landelijke-wow-dag-2017-2762

Nakamoto, S. (2008). *Bitcoin: A Peer-to-Peer Electronic Cash System.* bitcoin.org.

Odijk, S. v., & Bovene, F. v. (2014). *Circulair Bouwen: Het fundament onder een vernieuwde sector.* Amsterdam: ABN Amro.

Pauli, G. (2012). *The Blue Economy.* Amsterdam: Paradigm Publications.

Pilkington, M. (2016). Blockchain Technology: Principles and Applications. In E. Elgar, *Research Handbook on Digital Transformations.*

Pomponi, F., & Moncaster, A. (2016). Embodied carbon mitigation and reduction in the built environment - What does the evidence say? *Journal of Environmental Management 181*, 687-700.

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production 149*, 710 - 718.

Prendeville, S., Cherim, E., & Bocken, N. (2017). Circular Cities: Mapping Six Cities in Transition. *Environmental Innovation and Societal Transitions*.

Provenance. (2015, 11 21). *Blockchain: the solution for transparency in product supply chains*. Retrieved from Provenance: https://www.provenance.org/whitepaper

Ray, J. (2015, 11 2). *Blockchain and CRE: It's All About Speed To Transact!* Retrieved from LinkedIn: https://www.linkedin.com/pulse/blockchain-cre-its-all-speed-transact-jason-ray/

Redmond, A., Hore, A., Alshawi, M., & West, R. (2012). Exploring how information exchanges can be enhanced through Cloud BIM. *Automation in Construction*, 175–183.

Ritzén, S., & Ölundh Sandström, G. (2017). Barriers to the Circular Economy – integration of perspectives and domains. *Procedia CIRP 64*, 7 – 12.

Sahin, F., & Robinson, E. (2002). Flow Coordination and Information Sharing in Supply Chains: Review, Implications, and Directions for Future Research. *Decision Sciences 33*, 505-536.

Schillebeeckx, J., Soriano, M., & Teo, E. (2016). *Blockchain and Smart Contracts, Industry Roundtable Discussion Paper.* Singapore: Singapore Management University.

Seebacher, S., & Schüritz, R. (2017). *Blockchain Technology as an Enabler of Service Systems: A Structured Literature Review.* Karlsruhe: Karlsruhe Institute of Technology.

SenterNovem. (2007). *Industrieel, flexibel en demontabel bouwen (IFD).* SenterNovem.

Smith, G., Watson, K., Baker, W., & Pokorski II, J. (2007). A critical balance: collaboration and security in the IT-enabled supply chain. *International Journal of Production Research 45*, 2595-2613.

Spielman, A. (2016). *Blockchain: Digitally Rebuilding the Real Estate Industry.* Massachusetts: Massachusetts Institute of Technology.

Stahel, W. (2006). *The Perfomance Economy.* New York: Palgrave Macmillan.

Swan, M. (2015). *Blockchain Blueprint for a new Economy.* Sebastopol: O'Reilly.

Tapscott, D., & Tapscott, A. (2016). *Blockchain Revolution.* Penguin Random House UK.

Tasca, P., Thanabalasingham, T., & Tessone, C. (2017). *Ontology of Blockchain Technologies. Principles of Identification and Classification.*

The Circle Economy, IMSA. (2013). *Unleashing the power of the Circular Economy.* IMSA.

The Natural Step. (2017, 9 7). *Home*. Retrieved from The Natural Step: http://www.thenaturalstep.org/

Thomas, L. (2013). *Legal Issues Surrounding the Use of Digital Intellectual Property on Design and Construction Projects.* Washington: National Academy of Sciences.

Turk, Ž., & Klinc, R. (2017). Potentials of Blockchain Technology for Construction Management. *Procedia Engineering 196*, 638 – 645.

United Nations. (2014). *World Urbanization Prospects.* New York: United Nations.

United Nations. (2015). *World population prospects.* New York: United Nations.

van Sante, M. (2017). *Circular construction Most opportunities for demolishers and wholesalers.* ING.

Verberne, J. (2016). *Building circularity indicators an approach for measuring circularity of a building.* Eindhoven: Eindhoven University of Technology.

Vrijhoef, R., & Koskela, L. (2000). The four roles of supply chain management in construction. *European Journal of Purchasing & Supply Management 6*, 169-178.

Winans, K., Kendall, A., & Deng, H. (2017). The history and current applications of the circular economy concept. *Renewable and Sustainable Energy Reviews 68*, 825–833.

World Economic Forum. (2016). *Shaping the Future of Construction A Breakthrough in Mindset and Technology.* World Economic Forum.

Xu, J. (2016). Are blockchains immune to all malicious attacks? *Financial Innovation*, 2-25.

Yli-Huumo, J., Ko, D., Park, S., & Smolander, K. (2016). Where Is Current Research on Blockchain Technology?—A Systematic Review. *Plos One 11(10)*, 1 - 27.

Zaat, M. (2017, 6 15). *Torch schijnt nieuw licht op commercieel vastgoed sector*. Retrieved from ABN AMRO: https://www.abnamro.com/nl/newsroom/blogs/merijn-zaat/2017/torch-schijnt-nieuw-licht-op-commercieel-vastgoed-sector.html

Zheng, Z., Xie, S., & Dai, H. (2016). Blockchain Challenges and Opportunities: A Survey. *Web and Grid Services 1*, 1-25.

Zhong, R., Newman, S., Huang, G., & Lan, S. (2016). Big Data for supply chain management in the service and manufacturing sectors: Challenges, opportunities, and future perspectives. *Computers & Industrial Engineering 101*, 572–591.

Appendix

Appendix i: Interview guide

Topic list

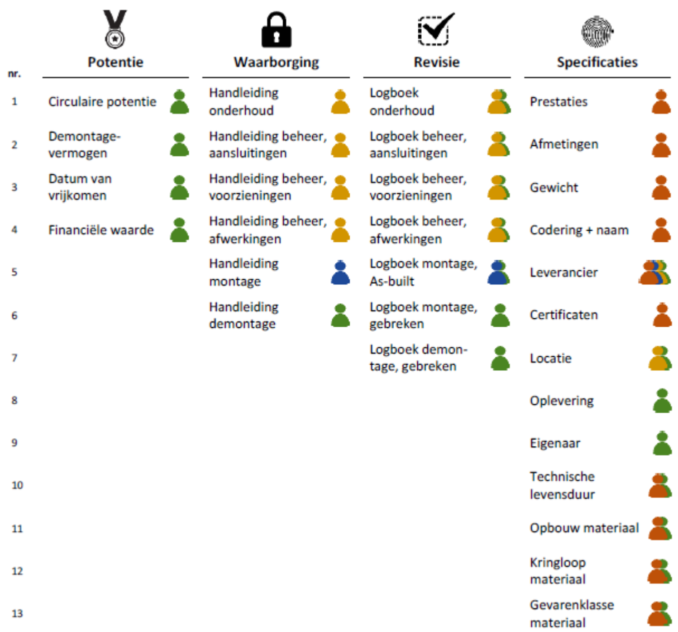
Interview designer

Introduction

Circularity goes beyond preserving in terms of sustainability. The accent of sustainability lays on lowering the energy consumption of buildings. In a circular economy there is a high focus on the reuse of materials and there is hardly any waste. For example during the design phase, consideration is given to the assembly in construction and the dismantling after use. The government has the ambition to realise a circular economy by 2050 that only uses reusable raw materials. One intermediate goal is a 50 percent decrease in primary raw materials use by 2030. The lack of an information and a material exchange system is currently blocking this exchange of materials between different actors. For this reason material passports are invented. Those material passports need to fill the gap of lack of information when a building is dismantled. With material passports information will be available of all the information of all the materials that are in the building. Within the lifetime of a building there are different stakeholders that could use a material passport. These stakeholders are visible in the figure below.

All these stakeholders use different types of information that is stored inside a material passport. An example of a material passport is shown in the figure below. The information inside the passport is stored on different levels, it goes from elements, to components, to materials. Every actor will use its own information of the material passport, this is also visible on the picture. On page 5 this figure is structured on which actor provides which information in the material passport and which actor will take which output from the system.

The interview will aim to identify the different barriers and opportunities that users and thus stakeholders of the material passport may experience.



Interview questions
Part 1: Verification material passport

1 Why is the use of a material passport important for your own process?

2 How is a material passport currently included in your own process?
  a. If not: How can you include material passports in your own process?
  b. What will be the added value?

3 Which barriers do you currently see that could prevent the use of material passports in your own process?
  b. Are these internal or external?

4 Which opportunities do you currently see that could stimulate the use of material passports in your own process?
  a. Are these internal or external?

Part 2: Experience LLMNT material passport
(If the interviewee has no experience with LLMNT, he is asked about how the process need to be structured for him to use the material passport in his own process)

5 Was it clear what the purpose of the LLMNT passport was before you were asked to share information?

6 How was the process structured when you gave information to the material passport?
  a. How efficient was the process of providing the information?
  b. How would you improve this process in an optimized situation?

7 What barriers/problems did you experience when you gave input to the material passport?
  a. Is this the same for all the data inputs?
  b. Are these barriers/problems internal or external?

* Example input streams from LLMNT material passport see page 4.

8 What are the requirements for the data that you take as output from the system before you can use the data it in your own process?
  a. Is this the same for all the data outputs?

* Example output streams from LLMNT material passport see page 4.

9 What opportunities do you see if you are able to use the information a material passport in your own process?

* Example output streams from LLMNT material passport see page 4.

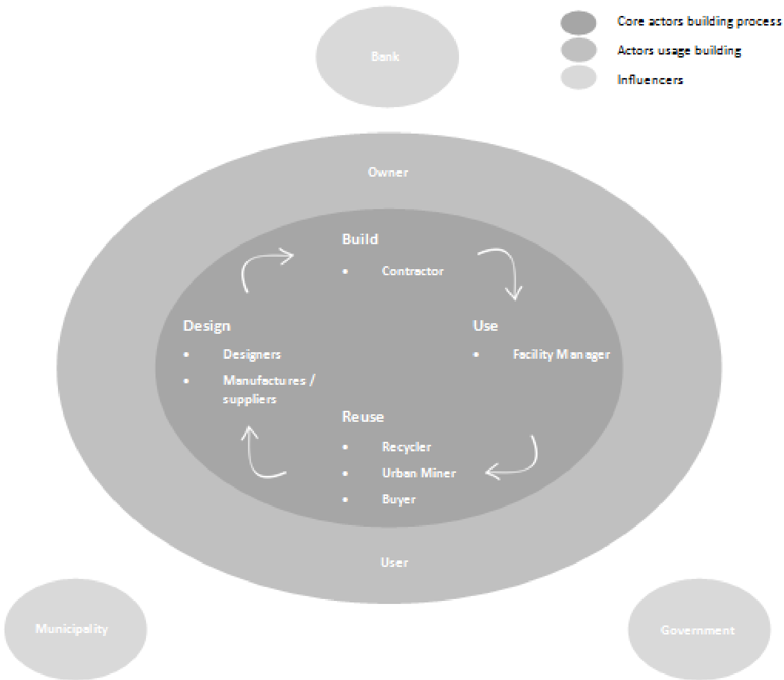
10 What are other important aspects of the system where material passports are stored?

Part 3: Finishing interview

11 Do you see some other barrier / opportunities for the implementation of material passports that are not mentioned yet?

12 Who are the most important actors in relation to the implementation of material passports?

a. How do you see the role of the bank in this situation?



Appendix ii: Input and output material passport for each actor

Table 18: Input and output material passport for each actor

	Design phase			Build phase	Use phase		Reuse phase	
	Designer	**Supplier**	**Advisor**	**Contractor**	**Facility Manager**	**Maintenance**	**Recycler**	**Urban Miner**
Input Material Passport	Location Manual dissassembly Code + Name	Manual Assembly Supplier Performance Size Weight Code + Name Certificates Technical Lifespan Build Up Material Re-use Loop Material Toxic Level Material		Log Montage	Log Management	Log Maintenance	Financial Value Log Dissassembly	Financial Value Log Dissassembly Supplier (as Urban Mine) Owner (as Urban Mine)
Output Material Passport	Performance Size Weight Code + Name Supplier Certificates Technical Lifespan Build up material Re-use loop material Toxic level material		Performance Size Weight Code + Name Supplier Certificates Technical Lifespan Build Up Material Re-use Loop Material Toxic Level Material	Manual Assembly Supplier	Manual Maintenance Manual Management Log Maintenance Supplier Location	Manual Maintenance Manual Management Log Management Supplier Location	Circular Performance Dissassembly possibilities Date Release Manual Dissassembly Log Maintenance Log Management Log Assembly Supplier Location Completion Owner Technical Lifespan Build-up Material Re-use Material Loop Toxic Level Material	Circular Performance Dissassembly possibilities Date Release Manual Dissassembly Log Maintenance Log Management Log Assembly Supplier Location Completion Owner Technical Lifespan Build-up Material Re-use Material Loop Toxic Level Material

Appendix iii: Coding scheme interviews

Table 19: Full coding scheme interviews

Opportunities

Clusters	#	Covering code	Supplier	Architect I	Architect II	Advisor	Contractor	Maintainer	Facility manager	Owner	Urban Miner	Recycler	Municipality
Provision of the information	1	More data continuity					x			x			
	2	Cost reduction								x			
Storage of the information													
Access of the information													
Quality of the information	1	Better data management	x			x		x	x	x	x	x	x
	2	Clear options for reuse					x		x	x	x		x
	3	Determining real value		x			x				x	x	
	4	Solving warranty issue		x	x		x	x					
Presentation of the information	1	More uniformity	x		x							x	
Process of giving information	1	Information request at the beginning	x								x		

Barriers

Clusters	#	Covering code	Supplier	Architect I	Architect II	Advisor	Contractor	Maintainer	Facility manager	Owner	Urban Miner	Recycler	Municipality
Provision of the information	1	Costs of providing	x	x	x	x				x			x
	3	Data not available		x			x		x		x	x	
	4	Companies do not want to be transparent	x	x				x					
	5	No overview lifecycle building					x	x					
	2	Confidentiality issues	x										
Storage of the information	1	Who has ownership?			x			x		x			x
Access of the information	1	Who has acces?	x			x				x			
Quality of the information	1	Quality assurance			x			x		x			
	2	No definition material passport		x			x						
Presentation of the information	1	Lack of uniformity	x			x	x		x	x			x
Process of giving information	1	Not involved from the beginning		x							x		
	2	No experimentation								x			

Requirements

Clusters	#	Covering code	Supplier	Architect I	Architect II	Advisor	Contractor	Maintainer	Facility manager	Owner	Urban Miner	Recycler	Municipality
Provision of the information	1	Easy handling	x	x					x				
	2	Reward system				x					x		
	3	Cooperation supply chain				x		x					
	4	Only necessary information									x		
	5	Predevined levels of detail	x										
Storage of the information	1	Clear ownership data	x	x									
	2	One data source								x			
	3	Security	x										
Access of the information	1	Predefined who has access	x						x				
Quality of the information	1	Validation		x		x			x	x	x	x	
	2	Immutable		x		x							
	3	Dependencies					x				x		
	4	Traceability									x		
	5	Dynamic during the lifetime		x									
Presentation of the information	1	Uniformity	x				x	x	x	x			
Process of giving information	1	Added value has to be clear	x			x							

Appendix iv: Combined table aspects material passport

Table 20: Combined table aspects material passport

	#	Covering code aspects	Opportunities	Barriers	Requirements
Provision of the information	1	Reward system		Costs of providing	Reward system
	2	Only necessary information		Data not availible / No overview lifecycle building	Only necessary information
	3	Easy handling			Easy handling
	4	Confidentiality		Companies do not want to be transparant	
	5	Cooperation supply chain			Cooperation supply chain
	6	Data continuity	Data continuity / Cost reduction		
	7	Standardisation		No definition material passport	
	8	Predefined levels of detail			Predefined levels of detail
Storage of the information	1	Ownership data		Who has ownership?	Clear ownership data
	2	One data source			One data source
	3	Security			Secuirity
Access of the information	1	Predefined who has access		Who has access?	Predefined who has access?
Quality of the information	1	Validation		Quality assurance	Validation
	2	Data management	Improved data management		
	3	Real value	Clear options for reuse		Dependencies
	4	Immutable	Solving warranty issues		Immutable
	5	Traceability			Traceabilitiy
	6	Dynamic during the lifetime			Dynamic during lifetime
Presentation of the information	1	Uniformity	Uniformity	Lack of uniformity	Uniformitiy
Process of giving information	1	Added value has to be clear			Added value has to be clear
	2	Information request at the beginning	Information request at the beginning	Not involved from the beginning	
	3	Experiment		Not experimenting	

Appendix v: Difference planned and final version material passport

Original set up material passport

nr.	Potentie	Waarborging	Revisie	Specificaties
1	Circulaire potentie	Handleiding onderhoud	Logboek onderhoud	Prestaties
2	Demontage-vermogen	Handleiding beheer, aansluitingen	Logboek beheer, aansluitingen	Afmetingen
3	Datum van vrijkomen	Handleiding beheer, voorzieningen	Logboek beheer, voorzieningen	Gewicht
4	Financiële waarde	Handleiding beheer, afwerkingen	Logboek beheer, afwerkingen	Codering + naam
5		Handleiding montage	Logboek montage, As-built	Leverancier
6		Handleiding demontage	Logboek montage, gebreken	Certificaten
7			Logboek demon-tage, gebreken	Locatie
8				Oplevering
9				Eigenaar
10				Technische levensduur
11				Opbouw materiaal
12				Kringloop materiaal
13				Gevarenklasse materiaal

Figure 32: Original set up material passport

Information final material passport

PASSPORT traptrede trap buiten 6806 [346531]	
Hoeveelheden	
Productomschrijving	Traptrede
Productnaam	X-LAM, 5S
Productcode	
Fabrikant	Derix gelijmde houtconstructies
NL/SfB-code	24.11
Materiaalgroep	i2
Materiaalomschrijving	Vurenhout; Lariks
Productdossier	
Eigenaar	ABN AMRO
Lengte	
Breedte	
Hoogte	
Volume	0.178 m^3
Conditie	Uitstekend
Gebreken	Geen
Verbindingen	Droog - Bouten en Schroeven
Datum plaatsing	01-09-2017
Gebouwlaag	Trappen en Liften
Verwacht einde gebruiksduur	Na 10 jaar
Datum vrijkomen	Nog onbekend
Status	Niet beschikbaar

Figure 31: Information final material passport

Confidential

For the full version of the appendix, please contact the author