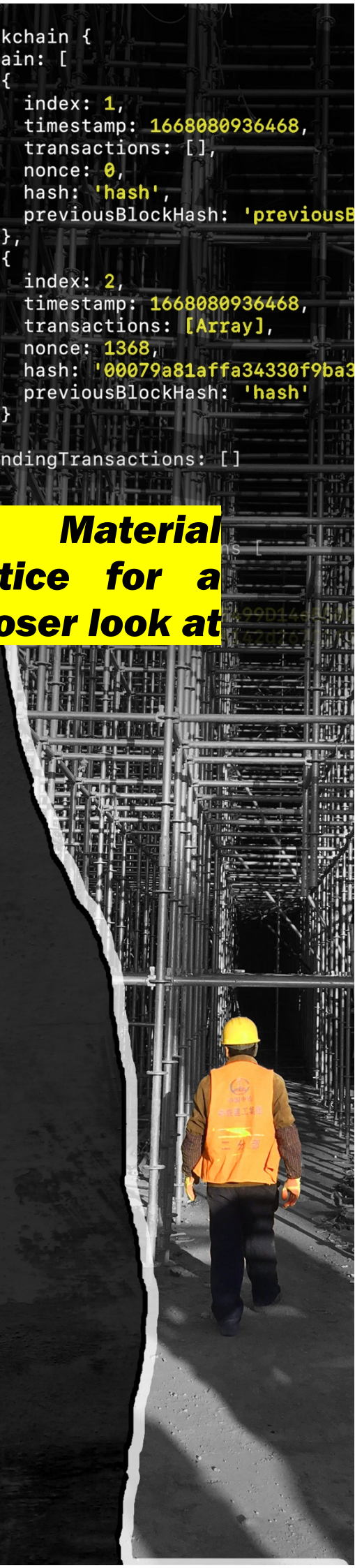


```
Blockchain {
  chain: [
    {
      index: 1,
      timestamp: 1668080936468,
      transactions: [],
      nonce: 0,
      hash: 'hash',
      previousBlockHash: 'previousB
    },
    {
      index: 2,
      timestamp: 1668080936468,
      transactions: [Array],
      nonce: 1368,
      hash: '00079a81affa34330f9ba3
      previousBlockHash: 'hash'
    }
  ],
  pendingTransactions: []
}
```

Integrating blockchain-based Material Passports (BBMPs) into practice for a circular built environment – a closer look at opportunities and barriers.

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Abstract

Recently, the academic community has acknowledged the theoretical potential for promoting circularity in the construction industry through the integration of blockchain technology and Material Passports (MPs). Yet, this potential remains mostly untapped in practice, contributing to a significant gap between theoretical frameworks and practical applications. This study therefore intends to explore the potential of blockchain-based Material Passports (BBMPs) by identifying their inherent opportunities and the barriers impeding their adoption into AEC-practice. Based on a comprehensive literature and practice review exploring the underlying concepts of Material Passports and blockchain technology, the research design features a multi-method approach with inductive and deductive logic of inquiry. Method one, semi-structured interviews, explore the first two research questions, followed by method two, a comparative case-study analysis of two early attempts at BBMPs, answering the last two research questions. The PESTLE framework of analysis served as the primary method of analysis to identify and categorize relevant BBMP-adoption barriers. The examined cases revealed a list of opportunities of BBMP-adoption in form of relevant use cases, as well as a final list of barriers for their adoption into industry practice. Aimed at a wide audience, this research contributes to academia and practice by synthesising previously studied aspects, studying early attempts at BBMPs in practice, and highlighting areas for future research by identifying opportunities and barriers of the adoption of BBMPs in AEC industry practice.

Keywords: Blockchain technology, Material Passports (MPs), blockchain-based Material Passports (BBMPs), circular economy (CE), circular transition

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Preface

Embarking on this master's thesis prompts me to reflect on my motivations for pursuing this diverse discipline called architecture, and my journey to this point. It represents a full-circle experience that I find deeply gratifying.

Like many, I originally aspired to be the next Peter Zumthor or Alejandro Aravena, architects I deeply admire, driven by my passion for design. Later, however, I went through a transformative period, where my ambitions shifted from naïve dreams to a sense of responsibility for our environment and the way we shape it.

Following my bachelor's degree, my work experience in the AEC sector allowed me to explore the complex mechanisms that significantly influence the built environment. I witnessed challenges faced by contractors, suppliers, and developers, which led me to acknowledge that architects are only one piece of the puzzle in shaping our existence on earth, both now and in the future – leaving me with many options to explore. On this journey I am fuelled by the pursuit for my own role within the sector and the quest for a more responsibly built environment.

Initially, my motivation for studying the architecture track 'Management in the Built Environment' at TU Delft was centred around the specific interest in 'resilience', especially the question of how to predict future changes as best as possible to design more adaptive cities. However, throughout the past two years I instead identified several other areas where progress is urgently needed to facilitate the AEC sector's transition to a sustainable future, enabling it to 'bounce forward' and prepare for what is to come. Part of this, I had the opportunity to discuss disruptive technologies such as 'BIM' and 'blockchain' with my guests in one of the episodes of the 'BOSScast', a podcast I hosted for the study association BOSS. Trying to shed light on these buzzwords I got to understand why professionals should embrace disruptive technologies, and their potential to help steer the sector towards a circular built environment.

Aiming to have a positive impact on an industry that I am passionate about, I therefore started to explore the intersection of disruptive technologies, circular economy, and the AEC sector, an industry that needs financial incentives to adopt overdue change. What, if only we could utilize the massive amounts of materials and components that are 'stored' in our buildings and cities? What, if only we could leverage the corresponding data of these materials and components?

In the motivational letter I once handed in to the admissions office of TU Delft I wrote "I am thinking about positioning myself in a mediating role between academia and the industry upon my graduation to help innovations be implemented.". Still, I see my future in this role and hope that this thesis can be the first step towards making a meaningful contribution.

With this thesis marking the end of my academic education, I would also like to take the opportunity to express my heartfelt gratitude to everyone who has accompanied me throughout this long and not-so-straight-forward journey. First and foremost, I want to thank my parents who have given me the freedom and time to find my way, supporting me throughout. Also, I want to thank my friends and siblings for being role models, companions, fellow sufferers and a constant source of joy – Estelle: you have kept me sane! And lastly, thank you to my supervisors Daniel, Sultan, and Brandon, for not only challenging me and enduring phases of up and downs, but also letting me dip a foot into your intriguing world of inspirational ideas with all IC-group related events.

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1 Introduction

In light of the recently advancing circular transition in the Architecture, Engineering, and Construction (AEC) sector (Adekunle et al., 2021; Mahpour, 2018), real estate developers are increasingly adopting circular building strategies such as the careful redevelopment of existing buildings to extend the service lives of materials, or modular design to ensure the disassembly and reuse of materials after a buildings end-of-life.

The vision of a circular built environment is led by the idea that instead of demolishing existing buildings to make way for new developments, they present an opportunity, acting as material banks that preserve valuable resources for future reuse. This way, the CE-model challenges the take-make-waste paradigm of the linear economy and emphasises sustainable resource strategies and value retention (Kirchherr et al., 2017). However, a pervasive lack of building information, especially about materials and components implemented in existing buildings, is proving to be a significant challenge for the circular transition (Honic et al., 2021), demonstrating that it cannot go without a digital one. The integration of advanced technologies into current industry practice promises higher efficiency and improved collaboration, inevitable for the establishment of truly circular value chains.

When developers buy old buildings and plan their renovation, they must make significant investments for building surveys to assess the structure's condition as well as register the materials and components in them, trying to determine what can be preserved and what must be demolished. Similarly, new buildings are only fit for disassembly and material recovery if relevant information about them is available.

Recognizing the significance of building information, Material Passports (MPs) have been proposed as the tool to close this information gap (Luscuere, 2017). Acting as digital representation of physical assets, Material Passports hold all relevant information about a physical asset throughout their entire lifecycle (Çetin et al., 2023) such as critical information about the asset's provenance, quality, and location, the same way a conventional passport describes the unique identity of a person. Although the set of information a Material Passport is supposed to hold, as well as the scope it should target (material – component – building – portfolio), remains subject to ongoing discourse (Çetin et al., 2023), the fundamental idea is uncontested: to ensure building and material information transparency and accessibility over long periods of time (Addis, 2012; Hunhevicz et al., 2023; Luscuere, 2017). Knowing the location, quality, and connection of objects allows for planned disassembly and costs savings for circular practices (Addis, 2012; B. S. Byers & De Wolf, 2023).

Depending on the level of sophistication of this information, MPs could also have significant impact on circular economy business models in AEC (Luscuere, 2017). They could provide the basis for optimizing processes such as the re-certification of materials ahead of disassembly as well as enable the accurate valuation of residual materials. Honic et al. (2021) also propose MPs could incentivize sustainability measures by helping building owners to determine the residual value of their properties and factor in residual material values in business cases. And lastly, Material Passports could enhance secondary material marketplaces such as the Dutch [materialenmarktplaats.nl](https://www.materialenmarktplaats.nl) (2024), where soon-to-be salvaged materials could be traded for the seamless integration in new projects.

However, for all these cases, it is imperative that the information stored on MPs is authentic, that it is validated, updated on a regular basis, and that it doesn't get lost throughout the long lifecycles of buildings and potentially changing ownership – in short: that it is true the moment it is needed.

Blockchain technology is a form of distributed ledger technology (DLT) and has been proposed to provide this single layer of truth to the set of information stored on a Material Passport as well as offer necessary infrastructure for the traceability of building information over the long lifetimes that characterise the building sector (Hunhevicz et al., 2023). There are various technical design options for DLTs as explained in detail by Hunhevicz & Hall (2020). However, the term “blockchain” has established

itself in academic and social discourse as a collective term for all kinds of DLTs and will henceforth be used to refer to DLTs in general.

Having originally been introduced by Nakamoto (2008) for the cryptocurrency Bitcoin as a mechanism for conducting online payments without intermediaries such as banks while maintaining a high level of security, blockchain refers to a decentralized system for transaction validation. In the context of Material Passports, it can be understood as the underlying infrastructure that helps to independently verify and validate the set of information stored on them. The technology ultimately removes the central authority that would conventionally take on this role and is characterized by its fundamental properties' immutability, non-repudiation, integrity, transparency, and equal rights for all participants as described by Hunhevicz & Hall (2020). These are meant to ensure trust in the completeness and correctness of the provided information, as well as provide security to the stored information by ensuring that it only exists once and cannot be tampered with (Q. Li & Wang, 2021; Yaga et al., 2019). As a result, the transparent recording of historic records of material information such as material provenance, maintenance records and tamper-proof logbooks is possible (Q. Li & Wang, 2021). Further, blockchain and smart contracts provide the potential to automate the recording of information through the integration with MPs and other digital technologies such as IoT devices, track and trace (T&T) technology, and BIM (Hunhevicz et al., 2022; J. Li et al., 2019; Ness et al., 2017). And lastly, decentralized data protocols can provide the potential to store MPs over long periods of time in a distributed and secure fashion, ensuring long-time accessibility of information (Hunhevicz et al., 2023).

1.1 Problem Statement

The AEC sector's transition towards a circular built environment is increasingly reliant on digital technologies that enable information transparency and accessibility, as well as data security and authenticity. With their distinct theoretical potential to transform how building material information is managed and leveraged, specifically data transparency and traceability of physical assets (Hunhevicz et al., 2023), blockchain-based Material Passports (BBMPs) stand out among them. However, despite their potential to synergize and promote the circular transition, there is a lack in sincere attempts to Material Passport and blockchain integration within the construction industry.

This CE-enabling potential remains untapped if not implemented in practice. As a result, there is a gap between theoretical potential and practical application when promising innovations as such are not implemented into everyday industry practice as can be seen in *Figure 1*.

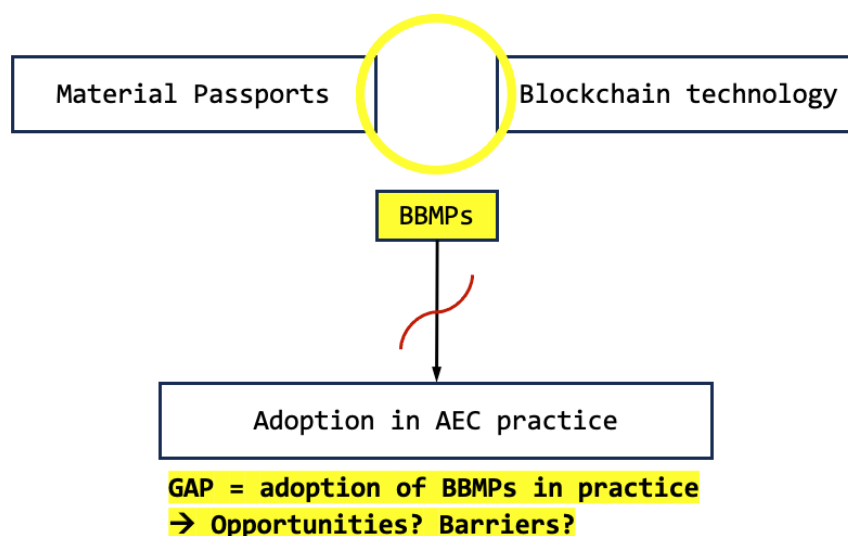


Figure 1 problem statement - lack of BBMP-adoption in AEC industry practice (author)

To bridge this gap and enable the adoption of blockchain-based Material Passports (BBMPs) to unlock their full potential, it is vital to understand the complexities of these technologies as well as the holistic understanding of their potential. This involves identifying the opportunities and benefits of BBMPs as well as understanding and addressing the barriers that impede their integration.

Therefore, this study aims to investigate the two aspects of BBMP adoption: the opportunities presented by BBMPs for the circular transition in the AEC sector, as well as the barriers that need to be addressed to implement them into industry practice. The main research question therefore is: *What is the potential for integrating blockchain-based Material Passports (BBMPs) into practice?*

Through the investigation of these two aspects, this research will help pave the way for the AEC sector to realise the transformative potential of blockchain technology and Material Passports, steering it towards a future that embraces circular economy principles enabled by technological advancement.

1.2 Aim

Consequently, the aim of this study is to make a meaningful contribution to the field of blockchain-based Material Passports (BBMPs), with a particular focus on discovering and prioritizing relevant use cases and challenges for their adoption into practice.

1.3 Research Questions

Recently there has been a growing interest in integrating blockchain and Material Passports (MPs) for a transition towards a circular built environment. Studies have largely focused on the technical aspects of their integration as well as their potential for the construction industry. However, little is known about the specific barriers and enablers of integrating BBMPs in practice.

The following main research question will address the adoption issues of blockchain-based Material Passports (BBMPs) and guide this research:

What is the potential of integrating blockchain-based Material Passports (BBMPs) into practice?

To answer this question a series of sub questions must be answered:

1. *What are barriers to Material Passports?*
2. *What are barriers to blockchain technology in AEC?*
3. *What opportunities do BBMP-providers see in the adoption of their technology?*
4. *What are challenges that current and early attempts at BBMPs face?*

The following conceptual framework contains the main concepts of the research questions and shows their connection:

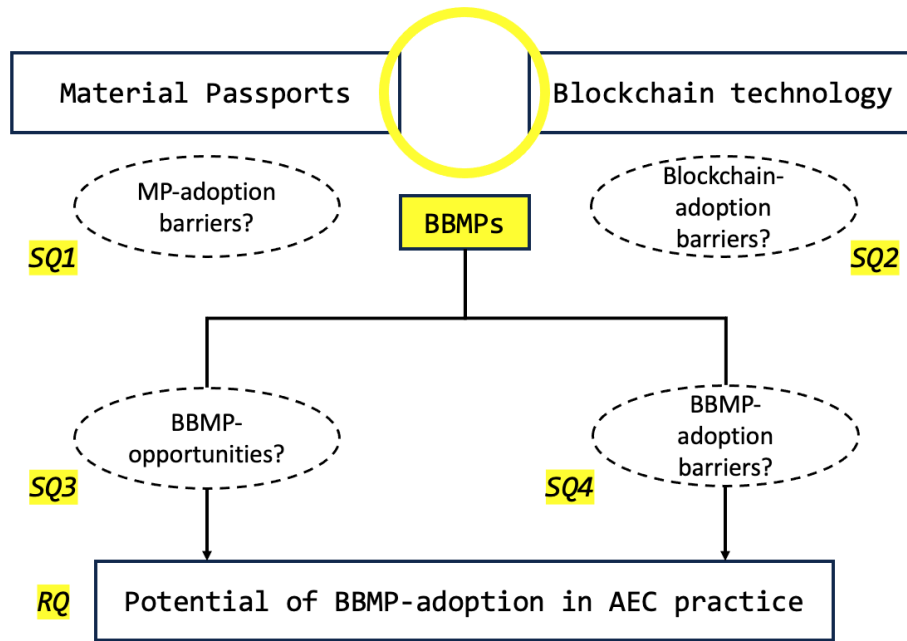


Figure 2 conceptual framework (author)

1.4 Relevance

The following will contextualize the specific relevance of this research in a larger social, professional, and scientific framework.

1.4.1 Scientific Relevance

The scientific relevance of this research will come from combining aspects that have been studied previously and satisfying the need for a first in-depth examination of commercial BBMP-projects to establish a comprehensive understanding of BBMP-opportunities and -barriers. This will provide a sound foundation for future research as well as for future decision making in industry practice.

Within the existing body of literature on Material Passports for AEC, most research focuses on the functions of MPs and the issues they address (Luscure, 2017), i.e. their potential for a transition towards a circular built environment (Honic et al., 2021). Prior research also discusses MPs technical integration and feasibility with other digital technology such as track-and-trace (T&T) technology (B. Byers et al., 2022) or BIM (Honic et al., 2019), and lastly their specific data requirements (Çetin et al., 2023).

Within the existing body of literature on blockchain technology in AEC, most studies focus on the technologies functionality as well as what problems it addresses (Yaga et al., 2019), i.e. its potential for a circular economy in construction (Q. Li & Wang, 2021). Further, research also frequently discusses the technical feasibility of blockchain technology for certain use cases in AEC, such as supply chain tracking (Wang et al., 2021), and the technical integration of blockchain with another technology: BIM, digital twins, and rarely MPs (Hunhevicz et al., 2022). Academics have also addressed the energy consumption necessary for token mining (Sedlmeir et al., 2020; Schinckus, 2020) as well as regulatory challenges around blockchain integration.

Adoption challenges of Material Passports and blockchain technology in AEC have also been discussed frequently, such as by Honic et al. (2021) in the case of MPs and by Q. Li & Wang (2021) in the case of

blockchain, including the development of frameworks for how to potentially overcome these (J. Li et al., 2019).

Currently, there is an absence of literature that investigates the overlap of these factors, particularly in terms of providing an in-depth examination of the opportunities for adopting blockchain-based Material Passports into AEC practice, as well as the barriers associated with their implementation. The evaluation and comparison of the first two BBMP-uses cases in practice will provide invaluable depth and context to this research and academic discourse.

1.4.2 Societal Relevance

The urgency of addressing climate change and achieving sustainability goals necessitates the decarbonization of the Architecture, Engineering, and Construction (AEC) sector, which accounts for almost 40% of energy and process-related emissions (IEA & GlobalABC, 2019). With the world's population predicted to approach 10 billion by 2050, the building stock is estimated to double (IEA & GlobalABC, 2019; UNDESA, 2022), highlighting the importance of reducing emissions and managing resource consumption.

This challenge emphasizes the importance of developing an industry-wide multi-faceted approach including innovative construction materials, establishing efficient production and construction processes, as well as building operation practices through the integration of emerging technologies. In addition, addressing the building industry's significant waste problem is particularly critical, since excessive material consumption and hazardous waste amplify the environmental impact of the building industry (Akinade et al., 2017; Formoso et al., 2002).

As a result, the current linear economic model, based on the assumption of unlimited natural resources and waste absorption capacity, is unsustainable (van Stijn, 2023). The circular economy (CE) provides a feasible alternative that focuses on the four resource principles of narrow (use less), slow (use longer), close (use again), and regenerate (make clean) (Geissdoerfer et al., 2017; Konietzko et al., 2020) to optimize material and product value while limiting resource inputs, waste, and emissions (Geissdoerfer et al., 2017). Amid this paradigm shift, digital technology such as blockchain-based Material Passports (BBMPs) can help the AEC industry adopt circular business models and capitalize on emerging economic opportunities (Ababio & Lu, 2023; Çetin et al., 2021; Hina et al., 2022; Xing et al., 2020).

2 Theoretical Background

The following literature and practice review has been conducted to analyse the state of the art in MPs relevance for AEC, blockchain technology's promise for MPs unresolved issues, and the adoption issue of both technologies in AEC. This approach helps to establish a foundation for this study by identifying and reviewing the relevant academic discourse surrounding blockchain-based Material Passports.

2.1 Material Passports' Relevance for AEC

As previously described in the introduction, literature repeatedly describes Material Passports (MPs) as an instrument for enabling a circular economy (CE) in the built environment (Byers & De Wolf, 2023; Hunhevicz et al., 2023), with some even praising them as CE's key enabler (Çetin et al., 2023; Hunhevicz et al., 2023). To understand the full potential of MPs, the following chapter will discuss their definition and characteristics, review the body of research currently available on the potential of MPs for the AEC. However, Material Passports also still have issues that impede them from unfolding their full potential. Therefore, this chapter will also explore unresolved issues of MPs as discussed in research.

2.1.1 Fundamental Concepts

Many scholars have defined Material Passports (MPs), all echoing the same canon: Luscuere (2017) initially identified Materials Passports (MPs) as a tool for stakeholders throughout the whole value chain of a building to document and track the full circular potential of materials, products, and systems by providing stakeholders with accurate information on various aspects of a products' circular design. Byers & De Wolf (2023) define Material Passports (MPs) as digital datasets that describe previously specified "characteristics of materials and components in products and systems that give them value for present use, recovery, and reuse", therefore also implying materials' circular value potential. Hunhevicz et al. (2023), on the other hand, simply characterise MPs as "digital datasets containing valuable information about materials and products" and later emphasise their key role in facilitating the circular transition.

Whatever the definition, four important dimensions stand out: the digital representation of a physical asset, the approach on a material-, component-, or systems-scale, the industry specificity, and the focus on enabling circularity. The following subchapters will elaborate on these dimensions in more detail.

2.1.1.1 Digital Representation

The dimension 'digital representation of physical assets' raises questions regarding what information Material Passports should hold. Çetin et al. (2023) analysed current approaches and discovered a lack of consistency in frameworks with varying terminology and content, as well as aggregation level, technology use, and maturity. This led to the identification of critical data requirements for Material Passports, summarized in *Table 1* (Çetin et al., 2023).

Table 1 Most relevant data points for MP content (adopted from Çetin et al. (2023))

Building General Information	Building name; Building location; Building year
Product General Information	Product name; Product code/no; Location in building; Installation date in building; Product documentation
Product Properties	Dimensions; Quantity; Composition of materials; Physical properties
Product safety, Health & Environment	Toxicity/hazardous substances; Untreated/treated; Renewable/non-renewable content
Product Operational Aspects	Condition & quality assessment; Expected service life or use times; Disassembly installation/manual; Assembly installation/manual
Product End-of-Life Aspects	Recycling potential; Reuse potential; Disposal options; Availability in future for reuse (time)

In practice, varying Material Passport solutions such as that of the start-up Madaster (*Appendix C & D*) demonstrate this variation. Madaster's Material Passport only cover 'Building General Information' and 'Product End-of-Life Aspects', leaving out all product-specific information such as 'Product General Information', 'Product Properties', 'Product safety, Health & Environment', and 'Product Operational Aspects'. This discrepancy emphasizes the necessity for a unifying MP framework regarding content and aggregation level (Çetin et al., 2023).

2.1.1.2 Scale

The question at what scale (dimension two) Material Passports should approach information provision is still open to ongoing discourse as practice experiments with different approaches. Nevertheless, literature rarely pays explicit attention to this, although it significantly impacts their content and functionality: a Material Passport on a building level typically visualizes a Life Cycle Assessment (LCA) for the property including an estimated reuse potential of materials in the building, visualising the potential monetary value of residual materials at the buildings end-of-life. Conversely, a passport on the component level can describe the materials extraction and reuse in detail, directly impacting the practical potential of MPs for circular practices.

As presented by Çetin et al. (2023), building-scale Material Passports are commonly used, examples being systems such as Madaster (*Appendix C & D*) (Madaster Foundation, 2024), Circularise, and CIRDAX. However, respondents of their study believe that a product-level approach may be more beneficial for thorough material tracking (Çetin et al., 2023).

Similarly, literature does not reflect a consensus on the ideal MP-scale either. Luscuere (2017) advocates a more comprehensive, systems-level approach, whereas Byers & De Wolf (2023) and

Hunhevicz et al. (2023) concentrate on materials and products. Çetin et al. (2023) suggest Material Passports may work on several levels, including an area-, complex-, building-, element-, product-, material-, and raw material-level (Figure 3).

	Digital Product Passports	Material Passports	Digital Building Logbooks
Scale	Product	Area; Complex; Building; Element; Product; Material; Raw material	Building
Industry	Cross-industry	(Mainly) Built environment	Built environment
Regulation	EU Ecodesign Directive	-	EU-wide Framework for a Digital Building Logbook

Figure 3 Differences and similarities between DPPs, MPs, and DBLs (Çetin et al., 2023)

Therefore, open questions that remain whether a DPP can be, if applied to a construction material, considered a Material Passport and whether Material Passports should be restricted to a specific aggregation level. Conversely, should MPs be restricted to the product-scale, it is questionable whether they contribute additional value beyond being DPPs for the construction industry. Potentially, existing tools such as DPPs or EPDs could fill this gap when issued for the construction sector specifically or when extended beyond a simple Life Cycle Assessment (LCA).

2.1.1.3 Industry Specificity

The third dimension ‘industry specificity’ is based on the unique complexity of construction materials and components life cycles (Luscuere, 2017). Buildings include a wide range of materials from numerous sources, making basic component lists insufficient for encouraging circularity. In addition, building material provenance tracking is often complicated by the involvement of many suppliers and sub-suppliers, as well as the composition of numerous substances. Furthermore, building materials must be enhanced by contextual knowledge such as location in the building and extraction potential (Luscuere, 2017). And finally, Luscuere (2017) describe a unique characteristic of construction materials to be maintained routinely during their service life in a building, demanding continuous monitoring to optimize their value and reuse potential. Material Passports can solve these difficulties by providing extensive data on material health, disassembly, and logistics.

2.1.1.4 Material Passport as CE-enabler

As mentioned initially, Material Passports have received extensive recognition for their ability to support circular economy (CE) practices in AEC – dimension four. In fact, the most distinctive dimension scholars and practice can agree on is their core intention to enable circularity in AEC.

The construction industry’s transition from a linear to circular economy is facing significant barriers, including information silos, a lack of digitalisation, poor stakeholder collaboration, insufficient knowledge sharing, and a lack of secondary material marketplaces (Byers & De Wolf, 2023; Torgautov et al., 2021). MPs have been proposed to solve these issues by making essential material data available as described previously, hence promoting circular policies (Luscuere, 2017).

2.1.1.5 Distinction of Passport Frameworks

Scholars such as Çetin et al. (2023) and Luscuere (2017) mention a variety of passport tools and other EU frameworks including Digital Product Passports (DPPs), Digital Building Logbooks (DBLs), and Environmental Product Declarations (EPDs). For clarity, Material Passports should be distinguished from these in addition to discussing the dimensions ‘digital representation’, ‘scale’, ‘industry specificity’, and ‘circularity implementation’.

Digital Product Passports, proposed by the European Commission as part of the Ecodesign for Sustainable Products Regulation (ESPR), aim at promoting environmental sustainability through information transparency for products and business models across all productive sectors (European Commission, 2022a). Consequently, they specifically focus on the product-scale (*Figure 3*). Within the framework of the ESPR, the Commission will release ‘delegated acts’ setting sector- and product group-specific rules for the products themselves, as well as the content of their respective DPPs (European Commission, 2022a). Eventually, Digital Product Passports are expected to overlap with Material Passports in the case of building materials.

Digital Building Logbooks are dynamic repositories that describe all relevant building data such as ownership and operational performance of a building, including energy use, and sustainability certificates. Whereas DBLs provide dynamic data required for building operation and management (European Commission, 2020), Material Passports mostly concentrate on static data.

Additionally, the International EPD (Environmental Product Declaration) System is often mentioned in relation to MPs (Luscuere, 2017), which manufacturers can independently apply for. As an internationally standardised sustainability label, it declares Life Cycle Assessments (LCAs) based on frameworks such as ISO norms (ISO 14040 within ISO 14025:2006 Environmental labels and declarations – Type III) for any product (EPD International, n.d.; ISO/TC 207/SC 3 Environmental labelling, 2006). Thus, Environmental Product Declarations could complement Material Passports rather than be a competing passport instrument.

2.1.1.6 Summary & Definition

Given the ambiguity regarding aggregation level, this thesis will align with recent publications such as Byers & De Wolf (2023) and Hunhevicz et al. (2023) and adopt the canon of practitioners in Çetin et al. (2023) recommending a product-approach. While documenting and tracking construction material and component information on a product-scale, Material Passports distinguish themselves from other passport tools given the industry specificity of the construction sector as well as their fundamental goal of enabling circularity in AEC.

For this thesis, the collective term Material Passport (MP) is therefore defined: a digital record that documents and tracks information about a physical asset in the built environment, such as a building-material, -product, or -component, with the purpose of enabling a circular built environment.

Figure 4 shows how Material Passports are understood in relation to other passport frameworks: a building consists of many materials and components, all with their own digital representation (Material Passport). The building itself is represented throughout building operation by a Digital Building Logbook that records operational information, which is also fed back to the MPs. An MP can be equivalent to a Digital Product Passport, if that DPP is extended in scope and functionality to track a building material throughout its long lifecycle. Both DPPs and MPs can integrate EPDs for environmental impact assessment.

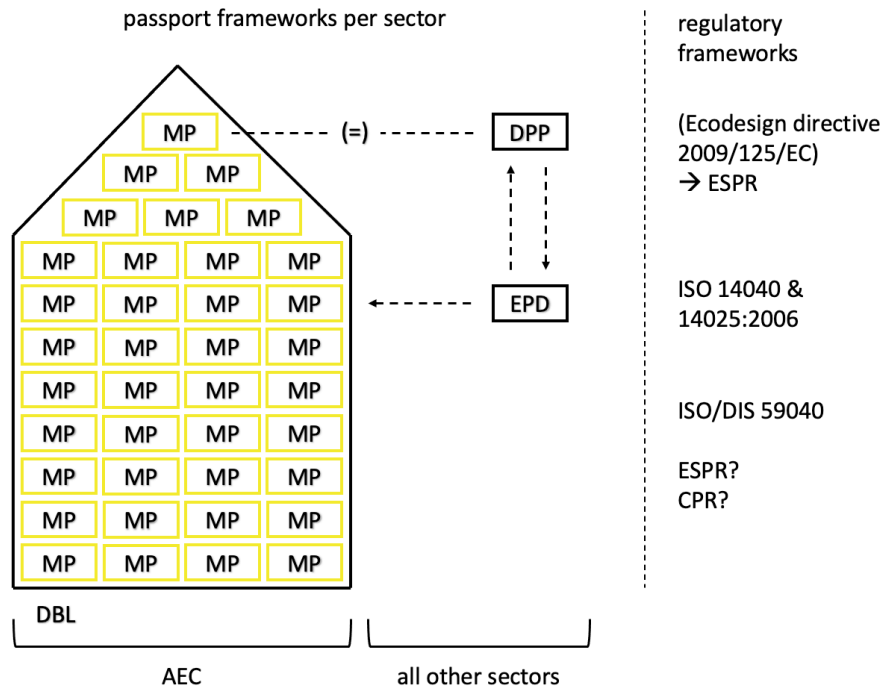


Figure 4 Material Passports in relation to other passport frameworks (author, 2024)

In a circular economy (CE), both product- and building-lifecycle timelines become circular. Building materials are derived from virgin materials, assembled to form a building, used throughout their service life, later disassembled and reused in another context. Building materials exceed their service life in a particular building. Likewise, Material Passports that accompany them exceed the time they support a Digital Building Logbook. Figure 5 represents this MP-DBL relationship on the building- and product-lifecycle timeline in a circular built environment.

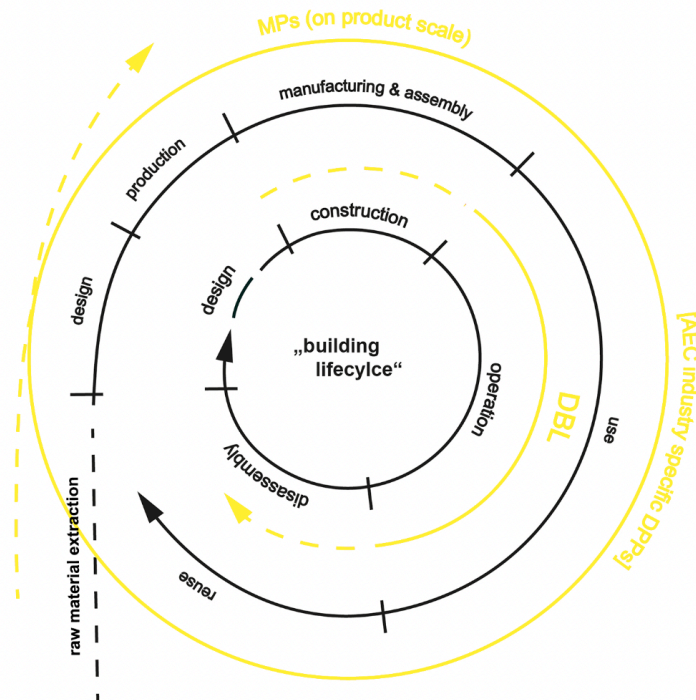


Figure 5 MPs in relation to DBLs, mapped on building- & product-lifecycle timeline in a CE (author, 2024)

2.1.2 Potential for AEC

Literature attributes Material Passports significant potential for the Architecture, Engineering, and Construction (AEC) sector in promoting the circular economy by providing material information transparency and accessibility. Material Passports contribute to resource preservation and the construction waste reduction (Luscuere, 2017). In addition, they incentivize stakeholder engagement (Çetin et al., 2023; Honic et al., 2019), design innovation (Honic et al., 2019), and innovative market mechanisms (Byers & De Wolf, 2023; Luscuere, 2017; Lüdeke-Freund et al., 2019). Demonstrating the full potential of Material Passports for the AEC sector, the following paragraphs will investigate these aspects in more depth.

2.1.2.1 Circular Economy Implementation

Three aspects are crucial in the implementation of CE in AEC: measuring the circularity level of a building (Çetin et al., 2023; Heisel & Rau-Oberhuber, 2020; Luscuere, 2017), value recovery and reuse of materials at the end-of-life of buildings (Çetin et al., 2023; Luscuere, 2017), and the tracking of materials throughout their lifecycle (Byers & De Wolf, 2023).

The first step in the circular transition is the ability to quantify and visualize the circularity level of a building. By making embodied carbon transparent, Heisel & Rau-Oberhuber (2020) i.e. propose Madaster's Circularity Indicator (*Appendix C & D*) could serve as a design tool to assess the environmental and economic effect of circular design and material choices, as a result encouraging design innovation such as design for deconstruction (Heisel & Rau-Oberhuber, 2020; Honic et al., 2019). Similarly, Material Passports can offer guidance for product design and help contractors or asset owners market the circular value of their products (Luscuere, 2017). Following design, Material Passports' transparency also plays an important part in incentivizing the responsible use of buildings and their materials throughout their lifecycle to minimize the loss in value.

Further, the ability to recover and reuse materials at the end of a buildings service life could be seen as the most critical component of the implementation of circular practices in AEC. After all, there is no circular economy without material recovery and reuse. If Material Passports supply information not only on 'building and material general information', as well as 'product properties' (*Table x*) such as quantities and dimensions, but also 'product operational and end-of-life aspects' such as accessibility for disassembly, transportability, warranty and guarantees, certification, product liability and insurance (Çetin et al., 2023), they make the planning of deconstruction and reuse possible (Addis, 2012; Luscuere, 2017).

The long lifecycles in the AEC sector, however, necessitate the tracking of materials throughout all lifecycle stages to ensure long-term access to and regular updating of this data (Byers & De Wolf, 2023; Luscuere, 2017). Hunhevicz et al. (2023) describe this as a central component to the circular transition. To establish an unmistakable link between the physical object and its digital record, as well as to automatically record relevant material data throughout their lifecycle, scholars propose the integration with track and trace (T&T) technology such as barcodes, quick-response (QR) codes, RFID, just to name a few, as well as Internet-of-Things (IoT) sensors and Building Information Modelling (Abhari & Abhari, 2019b; B. S. Byers & De Wolf, 2023; Tang et al., 2019). In a first proof of concept, Byers & De Wolf (2023) demonstrated the application of QR codes for the reuse of timber elements at the end of a building's life in a small-scale construction. In another example, Ness et al. (2017) demonstrated the integration of RFID, cloud technologies and Building Information Modeling (BIM) by creating a robust system for "on element" read and write data transfer for a dynamic data repository.

Whatever the track and trace technology, Material Passports, as data repository and information communication medium, provide the basis for construction supply chain tracking. MPs can provide the transparency and certainty required by asset owners, designers, manufacturers, contractors,

regulators, users or re-users at a buildings end-of-life in form of a complete historic data set about a component.

In summary, Material Passports help the construction industry transition toward a circular economy by offering an instrument for measuring and visualizing circular potential of properties, facilitating effective material recovery, and guaranteeing comprehensive lifetime material tracking and data management, ensuring data quality, actuality, and consistency.

2.1.2.2 Stakeholder Engagement

Material Passports compile information from several sources as well as provide specific information to different stakeholders at various phases of a building's lifecycle. Therefore, they necessitate user specific information (Luscuere, 2017), representing both a challenge and opportunity: current supply chains in AEC struggle with the accessibility of the right product data at the right time, but Material Passports can address this gap by supplying different users with information only relevant to them (Byers & De Wolf, 2023). Honic et al. (2019) argue they therefore naturally increase stakeholder engagement by requiring close collaboration among many parties, including academics, housing associations and developers, MP platform providers, circular economy consultants, reuse companies (material harvesters), architects, and other consultants (Çetin et al., 2023).

Honic et al. (2019) further demonstrate how stakeholder collaboration can be augmented by integrating Material Passports and BIM, referring to their BIM-supported Material Passport as the "binding agent" that facilitates cooperation possible and ensures stakeholder alignment. As discussed previously, design innovation will also benefit from increased communication and stakeholder collaboration.

Accordingly, Wijewickrama et al. (2021) discuss the emerging role of an information broker in the circular supply chain who manages information exchange and serves as the link between element information and digital platforms. Material Passports can be understood as the central vehicle for this information exchange (Byers & De Wolf, 2023).

2.1.2.3 Marketplace Mechanisms

As a result of Material Passports acting as a catalyst for market mechanisms, new business models and economic opportunities emerge along with the circular transition (Luscuere, 2017). Lüdeke-Freund et al. (2019) i.e. present six major circular economy business model (CEBM) patterns, which demonstrate how companies create value in a circular economy in the built environment, including repair and maintenance, reuse and redistribution, refurbishment and remanufacturing, recycling, cascading and repurposing, and organic feedstock. Material Passports support these as visualized in *Figure 6* in the example of the CEBM 'reuse and redistribution'.

BM Dimensions		CEBM design options										
Value proposition	Products	Repaired, refurbished, remanufactured, or recycled products	Reusable or recyclable products	Products based on recycled waste	Long-lasting products	Used products, components, materials, or waste as production inputs	Reusable or recyclable production inputs					
	Services	Facilitating collaboration	Take-back management	Customer education	Waste handling, processing	Product-/service-based functions	Maintenance, repair, control	Product-/service-based results	Upgrading	Auxiliary services		
Value delivery	Target customers	Quality-conscious customers	Cost-conscious customers	Green customers	B2B customers	B2C suppliers	B2B suppliers	C2C suppliers				
	Value delivery processes	Connecting suppliers and customers	Providing access to a product's functionality	Providing (product-based) services and results	Providing used products, components, materials, or waste	Taking back used products, components, materials, or waste	Sharing products, components, materials, or waste					
Value creation	Partners and stakeholders	Suppliers	Manufacturers	Retailers	Service providers	Public institutions	Collectors of products, components, materials, waste	Others (e.g., researchers)				
	Value creation processes	Maintaining or repairing products, components	Refurbishing or remanufacturing products, components	Recycling of products, components, materials, waste	Upgrading or upcycling of products, components, materials, waste	Reselling products, components, materials, waste	Taking back or recapturing products, components, materials, waste	Winning back base materials	Using used products, components, materials, waste as input	Matching over- and under-capacities	Designing products, components, materials	
Value capture	Revenues	Additional product revenue		Payments per unit of service	Payments for functions or results	Price premiums						
	Costs	Labor	Repair, maintenance, control	Waste handling, processing	Manufacturing	Resource inputs	Transportation, logistics	Supply risks				

Figure 6 MP contribution to CEBM pattern 'reuse and redistribution' (author, adopted from Lüdeke-Freund et al. (2019))

Changing market dynamics introduce new roles, such as the previously mentioned information brokers, MP-providers, and material harvesters (Byers & De Wolf, 2023). As an example, traditional waste-treatment companies such as Veolia or Remondis reposition themselves to become material harvesters (REMONDIS SE & Co. KG, 2024; REMEX GmbH, 2024; Veolia Environnement SA, 2024), while platforms like restado in Germany (Concular GmbH, 2024), Material Reuse Portal in the UK (ReLondon, 2024), or the initiative materialenmarktplaats.nl in the Netherlands (materialenmarktplaats.nl, 2024) position themselves as digital marketplaces for secondary materials.

Digital markets are gaining in importance as well. Material Passports collect huge quantities of data, increasing in complexity with the advancement of the technology and its integration with other digital technologies, necessitating improved digital storage solutions and dynamic repositories (Byers & De Wolf, 2023). As a result, big data analytics forecasting material availability as well as just-in-time delivery models become possible, enabling the monetarization of building data and revolutionizing conventional supply chains (Byers & De Wolf, 2023).

Material Passports further enable building servitization models such as Products-as-a-Service (PaaS) or Product Service Systems (PSS) in which manufacturers lease their products instead of transferring the ownership, retaining responsibility for material recovery and end of life treatment (Azcarate-Aguerre et al., 2022; B. S. Byers & De Wolf, 2023). Similarly, investors could buy the ownership of single components in buildings as opposed to the whole property, again prompting new business models. However, this is still very much in its infancy and will be discussed further in the following chapter 'unresolved issues'.

2.1.2.4 Material Passports' Potential for AEC Summary

Material Passports have found to be essential drivers for a circular built environment due to various characteristics, such as providing accurate material information, enabling the visualization a building's circularity as well as material recovery and reuse. Augmented by track and trace technology, they can ensuring long-term data accessibility and actuality. Beyond circular economy practices, Material Passports promote stakeholder engagement by enhancing collaboration and knowledge-sharing as well as empower AEC professionals to make knowledgeable design and material choices, thus also incentivizing design innovation. Furthermore, by emphasizing the residual value of materials, enabling business models such as Product-as-a-Service (PaaS), and creating new market parties like information brokers and material harvesters, Material Passports create new market dynamics. In summary, it is the ripple effects from their successful integration that makes Material Passports a transformative tool for the AEC industry in its transition towards a circular economy.

2.1.3 Unresolved Issues?

As much as Material Passports bear potential for the AEC industry, there are also still unsolved challenges that prevent their widespread adoption. Most literature that discusses prospective added value to the construction sector through Material Passport integration addresses unresolved issues in the same course. Further, a look at practice reveals a dispersed landscape of passport instruments with various use cases and low rates of implementation in everyday practice (Çetin et al., 2023).

The barriers that currently challenge the widespread implementation of Material Passports are roughly split into external and internal factors. Issues inherent to the technology concern their interoperability with processes and other digital technologies, including a lack of standardization in content, data storage and modelling, budgetary restrictions, as well as legal and regulatory gaps (carrot vs. stick approach).

External factors concern broader AEC industry characteristics, including sector's slow adoption of circular practices and technology adoption in general, the intricacy of the building supply chain, and a lack of material and process standardization in construction. Although these barriers are not restricted to Material Passports, they have a big influence on their adoption into practice.

2.1.3.1 Lack of Content Standardization

Crucial for the widescale adoption of Material Passports is a uniform data template, as discussed previously (Çetin et al., 2023). However, every provider takes a unique approach to scope and information aggregation, impacting Material Passport content and complicating the widespread adoption of Material Passports in construction practice.

Material Passports at the building scale, such as in the case of Madaster (*Appendix C & D*), may compile a variety of general data by linking components in a 3D model to public databases. Although sufficient for conducting Life Cycle Assessments (LCAs) and visualizing a building's circular potential, this level of detail may not satisfy the precise information needs for material recovery and reuse, such as 'Product Properties', 'Product safety, Health & Environment', 'Product Operational Aspects', and 'Product End-of-Life Aspects' (Çetin et al., 2023). In addition, building-scale Material Passports maintained on a platform behind a paywall might not address the isolation of information in silos, one of the industry-wide barriers to the circular transition of the AEC sector (Byers & De Wolf, 2023). This ambiguity over content can diminish Material Passport's value proposition.

2.1.3.2 Digital Process: Data Storage and Modelling for Material Passports

Another prevalent issue Material Passports encounter is deficiencies in current data storage and modelling practices, particularly given the long lifecycles of buildings and materials in construction compared to other productive sectors. Data storage solutions vary in design, capacity, management capabilities, and flexibility, lacking a uniform framework.

Byers & De Wolf (2023) emphasise successful data management systems must incentivise continuous data input to prevent data scarcity and preserve data integrity. For this, several key characteristics are relevant, such as long-term data storage for the successful tracking of building components throughout long lifecycles, a dynamic repository architecture to allow automated and (near)live data input, efficient throughput for the processing of vast amounts of data, as well as long-term accessibility and a clear distribution of read- and write-permissions. Further, Byers & De Wolf (2023) highlight data security and tamper-proofness for the reliability and authenticity of Material Passports and their stored information, Material Passport's interoperability with other MPs, IoT devices, BIM software, or platforms such as material marketplaces for the usability of information across systems and formats, and scalability, meaning the ability to enhance Material Passport information by linking other data and establishing a relational database (Byers & De Wolf, 2023).

Literature has begun to address these problems in isolated cases. Honic et al. (2021) demonstrate the interoperability and dynamic integration of Building Information Management (BIM), Material

Passports, and traditional data spreadsheets, whereas Tang et al. (2019) explore the integration of BIM and IoT for a dynamic repository in a relational database structure. However, the authors report interoperability issues and recommend further research regarding data integration and management standards (Tang et al., 2019). And lastly, Byers & De Wolf (2023) compare several data storage and management structures for QR Code-based Material Passports, discussing their respective advantages and limitations:

Spreadsheets, initially intriguing due to their simplicity and accessibility, face numerous obstacles that restrict its use in complicated settings such as storage capacity and throughput limitations regarding large data volumes and multiple data types, difficulties regarding ownership and data integrity due to an unclarity about read- and write-permissions, particularly in collaborative contexts with multiple stakeholders, as well as scalability. These issues underscore the need for alternative, perhaps decentralized, methods of storing and maintaining component data (Byers & De Wolf, 2023).

Web hosting, such as GitHub Pages and HTML, offer a flexible design platform with less constraints on storage capacity and scalability. Each building component can be dedicated its own website with the option to integrate additional documents for download or redirects to manufacturer platforms, representing relational databases and improving accessibility of material information (Byers & De Wolf, 2023). However, updating of data requires coding skills, effectively representing a technological barrier and potentially leading to inconsistent data.

NoSQL database, the so-called “MERN stack”, integrated into a full-stack Material Passport platform provides a complete solution for creating dynamic websites and web apps, consisting of four distinct technologies that each serve a specific purpose along the data management process: “MongoDB” as storage solution, “Express” handling server-side operation, “React” for the user interface, and “Node.js” executing the server-side JavaScript (Byers & De Wolf, 2023). Leveraging the advantages of each integrated technology is what makes the MERN stack attractive, enabling flexible, document-oriented data management with efficient throughput and equal access to read- and write-permissions, as well as data hosting on multiple serves, effectively promoting scalability. Finally, the underlying data format BSON is said to be highly interoperable across many platforms and data systems, making it convenient to integrate with other technologies (Byers & De Wolf, 2023).

On the other hand, unresolved issues include data consistency and long-term storage, data integrity, security and tamper-proofness. Despite the application of security features like access restrictions and encryption, open read- and write-permissions could enable unauthorized or false data modifications, if not handled appropriately. Further, Byers & De Wolf (2023) warn that data input flexibility could also oppose Material Passport standardization and raise concerns about privacy.

While isolated examples demonstrate potential, no one data management solution currently achieves all the requirements for the mainstream adoption of Material Passports, including long-term storage, flexibility, efficiency, accessibility, data integrity, security, interoperability, and scalability.

2.1.3.3 Lack of Financial Incentives

Another Material Passport-internal factor inhibiting their wide-scale adoption for a circular transition in AEC are a lack of financial incentives provided by them to overcome budgetary constraints related to research and development in the sector. The industry has not yet widely adopted circular practices and Material Passports are still grappling with clarifying their position in relation to other passport instruments and tools like certificates. According to Byers & De Wolf (2023), the high implementation costs of Material Passports are not yet sufficiently compensated for. Most businesses find building information stored on Material Passports useful, but their limited budget for data collection prevents them from taking the initiative.

Govindan & Hasanagic (2018) as well as Guerra et al. (2021) support this observation, highlighting more general AEC-specific technology adoption issues such as high upfront costs, limited initial profit incentives, and unknown long-term financial rewards of materials' residual values. As a result, there is little intrinsic motivation to set up a functional Material Passport infrastructure, emphasizing the need for improved legal frameworks to facilitate the shift.

2.1.3.4 Regulatory and Legislative Gaps

Material Passports struggle with the right balance of financial incentives and supporting regulation, a lack of push factors as well as pull factors. Current regulatory frameworks fail to successfully promote the adoption of MPs, particularly in areas such as content standardisation and data management. In addition, Azcarate-Aguerre et al. (2022) discuss unclarity about ownership of data and salvaged materials, inhibiting the potential of novel business models such as Products-as-a-Service (PaaS).

Using regulatory frameworks as an active push factor towards more sustainable behaviour is not unprecedented. As an example, the “Besluit bouwwerken leefomgeving” from the Netherlands mandated energy labelling for buildings as of January 1st, 2023 (Rijksoverheid, 2018). As a result, AEC professionals, especially asset owners, were forced to invest in sustainability measures for compliance. However, it remains to be discussed whether Material Passports should be regulated on a national, European, or international level.

To counter the prevalent lack of content standardisation, Çetin et al. (2023) propose a framework with the potential to not only help practice, but also inform future legislation. Material Passports could also become subject to trans-national regulation currently under development, such as the ISO/DIS 59040 “Circular Economy – Product Circularity Data Sheet”, aiming at offering transparency and quality of circular economy related data when purchasing or supplying products (ISO/TC 323 Circular economy, 2024). On a European level, Material Passports could also become part of the Ecodesign for Sustainable Products Regulation (ESPR) in form of a delegated act for construction materials (European Commission, 2022a), in which case they would be absorbed by the DPP-concept. Another option could be the Construction Products Regulation (CPR), harmonizing rules for the EU market entry of construction products (European Commission, 2022b). The CPR could i.e. mandate Material Passports for every construction product in the EU market like it encourages DBLs, and similar to the “Besluit bouwwerken leefomgeving” mandating energy labels.

Next to content and data management, the circular transition and Material Passport implementation is also impacted by regulation preventing the emergence of novel business models such as Products-as-a-Service (PaaS) (Azcarate-Aguerre et al., 2022). The servitisation of buildings and their components, as proposed by PaaS, questions the status quo in how legislation conceptualizes ownership in the built environment. Basically, the rule of *accessio* in Dutch property law assumes, based on the distinction between movables and immovables, that everything that is fixed property on a particular land owned by a specific party is, by definition, a part of that owner's "real estate" (Ploeger et al., 2019). As a result, current legislation is indirectly inhibiting the adoption of Material Passports, because it prevents the emergence of business models reliant on the information made available by Material Passports, which create significant financial incentives for their large-scale dissemination.

The adoption of Material Passports could be significantly assisted by regulatory frameworks, ensuring standardization, enabling novel business models, and integrating Material Passports into larger digital and circular economy frameworks.

2.1.3.5 Summary Unresolved Issues of Material Passports

Bearing considerable promise for the AEC sector, Material Passports still encounter several unresolved issues that prevent their widespread use. Among their most important issues are factors inherent to

the technology, such as a lack of content standardisation, and a lack of a sufficient data management frameworks. Amplified by unclarity regarding their definition, these technological barriers hinder the integration of Material Passports into existing practice. Moreover, the barriers discussed in this chapter encompass economic aspects such as a lack of financial incentives and budgetary constraints that discourage stakeholders to embrace the technology. Missing financial incentives are compounded by the absence of supporting regulation.

For Material Passports to successfully promote circular economy principles in the AEC industry, it is imperative that the industry coordinates efforts in the areas of Material Passport standardisation, -incentivisation, and -education. Although some issues may only be solved by time, proactive action can undoubtedly accelerate this process.

2.2 Blockchain & AEC

After having extensively explored Material Passports, the following chapter will discuss another innovative technology that holds disruptive potential for the Architecture, Engineering, and Construction (AEC) sector. An extensive description of blockchain technology and its benefits for AEC is beyond the scope of this research, but can be found in *Appendix J*. After a brief introduction to blockchain technology, this chapter will discuss the general potential of blockchain for AEC, and its potential to solve some of the issues Material Passports currently struggle with, including characteristics such as blockchain technology's ability to ensure data transparency and process automation as well as its revolutionising potential for contractual agreements and data management practices. Lastly, the chapter will explore some possible reasons for the currently limited implementation of blockchain-based Material Passports (BBMPs) in AEC.

As introduced earlier, blockchain technology is a form of Distributed Ledger Technology (DLT) that emerged as a mechanism for conducting online payments without intermediaries such as banks while maintaining a high level of security. Although, from a technological point of view, Distributed Ledger Technology (DLT) has evolved since its first introduction through Nakamoto (2008), the name "blockchain" has become synonymous with any form of DLT and will henceforth be used throughout this research. Apart from cryptocurrencies, blockchain has expanded to multiple other industries, with proven use cases in supply chain tracking across several industries as discussed by Beck et al. (2023), or digital wallets for identity management systems such as the recent COVID-19-certificates (Sedlmeir et al., 2021). Likewise, blockchain has since also made its way into the AEC sector, where academics see a diverse range of potential for its application.

2.2.1 Fundamental Concepts

Blockchain technology is a decentralized system for facilitating value transactions of various kinds within a peer-to-peer network that avoids a trusted third party as regulating authority. Transferred values can include data sets, records of ownership, proof of certifications, records for supply chain tracking and many more.

Blockchain is set up in a three-layer technology stack: the Internet Layer as a base-infrastructure, the Protocol Layer, consisting of an immutable ledger which is distributed among nodes in a peer-to-peer network and regulated by consensus mechanisms such as proof-of-work or proof-of-stake. These layers work together to produce the fundamental properties of blockchain: immutability, non-repudiation, integrity, transparency, and equal rights for all participants (Hunhevicz & Hall, 2020). So long as the ledger can process code, a third layer, the application layer, can be set up for the execution of smart contracts.

2.2.2 Blockchain-potential for AEC

Literature neither categorically praises nor denies the potential of blockchain technology for AEC practice. Rather, it reasonably discusses different cases in which the AEC sector benefits from blockchain integration. Hunhevcz & Hall (2020) and Q. Li & Wang (2021) i.e. illustrate blockchain's value proposition regarding improvements in efficiency, collaboration, and sustainability. At the same time, scholars highlight new obstacles presented by blockchain, such as legal, technological, and collaboration concerns that need to be addressed (J. Li et al., 2019).

The choice for or against blockchain technology should be made on a use case basis, considering the particular demands of each case. Based on the decision framework presented by Hunhevcz & Hall (2020), the need for a blockchain infrastructure in AEC comes down to several factors such as the complexity of multi-stakeholder collaboration and their respective relationships, the need for transparency and trust in collaboration and whether stakeholders trust an intermediary to establish these, the need for record-keeping and compliance, and an increasing need for automation.

2.2.3 Solutions for Material Passports?

Material Passports have emerged as a viable tool to establish circularity practices in AEC through making material and component data visible as well as facilitating the traceability of physical assets throughout their value chain. However, several unresolved issues remain as discussed previously. These include both external and internal barriers, such as a lack of Material Passport content standardization, inadequate data storage and modelling, and a lack of push and pull factors for industry-wide dissemination. Meanwhile, it has been suggested that blockchain technology could provide several benefits for the AEC industry all aimed at improving efficiency, collaboration, and sustainability practices in the sector. Some scholars have further proposed the integration of both technologies, such as Q. Li & Wang (2021) and Hunhevcz et al. (2023), highlighting benefits such as the independent verification of transactions (i.e. Material Passport data entries), the ability to track environmental performance and issue automatic payments via smart contracts, as well as establishing data storage safety and long-term data accessibility by leveraging the decentralized nature of a Web3-storage infrastructure (Hunhevcz et al., 2023). Blockchain can also award every Material Passport a unique identity by hashing a unique identifier (UID) added to the passport on the ledger of a blockchain network. This enables the explicit and undisputable connection of ownership and use rights between the material and its owner, which is essential for the trade with secondary materials and more. This poses the question how blockchain technology can help overcome the unresolved issues of material passports described in the previous chapter. Therefore, the following section will discuss the potential of blockchain to aid Material Passports in their adoption by addressing some of the barriers they currently face.

2.2.3.1 Material Passport-content & Data Validation

The lack of a unified framework as described by Çetin et al. (2023), including terminology and content, aggregation level, technology use, and maturity is not directly something blockchain technology can solve. However, blockchain can predefine the content that is automatically generated. This is necessary for example if Material Passports are integrated with IoT-devices for automated environmental assessment criteria tracking as implied by Q. Li & Wang (2021) or make use of smart contracts for the automatic execution of terms of a contract based on pre-set criteria (J. Li et al., 2019). The prevalent confusion about what a Material Passport is, at what scale it should aggregate information, and thus what content it specifically holds remains to be solved independent of blockchain technology integration.

More importantly for the topic of content, however, is data validation. As discussed extensively in *Appendix J*, blockchain technology naturally improves the reliability and authenticity of Material Passport-data due to its fundamental properties. Every new data entry on a blockchain-based Material Passport would be verified by the independent network of nodes, which must reach consensus to

approve the record, eliminating an intermediary and the likelihood of data tampering or fraud in the process (Hunhevicz & Hall, 2020). In addition, encrypting data records ensures immutability and non-repudiation, resulting in stakeholders' trust in the accuracy and validity of the information stored on a Material Passport (Q. Li & Wang, 2021).

2.2.3.2 Digital Storage & Modelling (Data Management)

Digital storage and modelling, as discussed extensively by Byers & De Wolf (2023), who explored the strengths and weaknesses of three conventional data storage architectures, can be enhanced by blockchain technology. The main issues with conventional data management structures are storage capacity and design flexibility, throughput, long term storage, a dynamic repository that allows and incentivizes continuous data input, data accessibility, data security and tamper-proofness, homogenous data input and accuracy, and scalability (Byers & De Wolf, 2023).

Decentralization known from blockchain technology has been proposed to effectively solve storage capacity, storage design flexibility, and long-term stability and availability by distributing data across a network of peer-to-peer nodes (Hunhevicz et al., 2023). As the storage of large sums of data on a blockchain ledger significantly increases the computational effort required for executing consensus mechanisms such as proof-of-work, however, it would reduce throughput and make data storage very expensive. Therefore, data is not stored on the blockchain itself. Instead, Hunhevicz et al. (2023) recommend a two-layered approach in which data (Material Passport content) is saved in a Web3 storage solution such as IPFS (InterPlanetary File System), which makes use of decentralization as described, and only a unique identifier (UID) linked to the passport document is hashed on the blockchain, therefore decreasing the on-chain footprint, and increasing efficiency. This setup demonstrates the interoperability of Web3 storage solutions and blockchain technology, making it fit for scalability.

Other benefits include their ability to establish relational databases as described by Byers & De Wolf (2023) and Tang et al. (2019), long-term data accessibility while also preserving data security, the customization of access rights via smart contracts, making sure that data is only visible to authorized participants, as well as the seamless exchange of data ownership via Decentralized Applications (DApps) (Hunhevicz & Hall, 2020). And lastly, decentralization also reduces the possibility of fraud and data manipulation (Hunhevicz & Hall, 2020). When combined with encryption, it guarantees data security, tamper-proofness, and the immutability of records (Q. Li & Wang, 2021).

In addition, blockchain's ability to include financial incentives through the introduction of tokens can actively stimulate ongoing data entry, minimizing data paucity and creating a dynamic repository. This dynamic structure is fundamental for integrating real-time data provided by IoT devices and the execution of smart contracts (J. Li et al., 2019).

Overall, the capabilities of blockchain have the potential to improve the security, reliability, and efficiency of Material Passports as a whole, in addition to solving data modelling issues of existing storage solutions.

2.2.3.3 Marketplace Mechanisms & Material Ownership (Push & Pull Factors)

Blockchain may address the current lack of financial incentives provided by Material Passports and create pull factors for encouraging their dissemination. The fundamental properties of blockchain technology improve the reliability and authenticity of content on Material Passports, such as material quality, quantities, and maintenance records (Q. Li & Wang, 2021). This creates a reliable basis for determining residual values of materials and establishing confidence in valuation processes, catalysing the emergence of new revenue streams such secondary material marketplaces.

Further, blockchain and Material Passport integration can make building and material servitization such as Product-as-a-Service (PaaS or PSS) possible by unmistakably establishing material or component ownership through tagging a Material Passport with a unique identifier (UID) that is hashed on a distributed ledger (J. Li et al., 2019). These models have the potential to revolutionize the delivery and monetization of goods and replace traditional ownership with flexible leasing or renting arrangements (Azcarate-Aguerre et al., 2022). PaaS can therefore provide a dynamic market for material ownership that will increase profitability and sustainability of assets and indirectly incentivize the adoption of Material Passports.

On the other hand, blockchain cannot directly introduce push factors by mitigating the lack of legal frameworks. Nevertheless, said novel business models (PaaS/PSS) question the current status quo in property law (Azcarate-Aguerre et al., 2022) and subsequently will encourage legislators to re-evaluate regulatory frameworks.

2.2.3.4 Blockchain Solutions for MPs Summary

By improving data quality, transparency, and transaction security, blockchain technology offers important answers to the unsolved problems Material Passports currently face in their adoption in AEC, mostly surrounding Material Passport-inherent barriers. Not only enhancing Material Passports' operational capabilities, blockchain technology offers financial incentives that might have the potential to fundamentally change industry business paradigms. Despite the advantages, the construction sector is not experiencing a lot of attempts to integrate blockchain technology with Material Passports. Therefore, the next chapter will examine possible barriers for the adoption of blockchain-based Material Passports (BBMPs).

2.3 Why no Implementation?

The following chapter will explore the barriers for a widespread implementation of blockchain-based Material Passports (BBMPs) in the construction sector. As the barriers are manifold, it seems reasonable to explore the barriers to the underlying concepts of this research: first, the chapter will look at general barriers related to AEC industry inherent characteristics to develop an understanding for the environment of technology adoption at large, followed by Material Passport- and blockchain-specific barriers.

2.3.1 General Barriers & the AEC Industry Adoption Issue

The Architecture, Engineering, and Construction (AEC) sector is frequently facing substantial challenges in the adoption of not only blockchain or Material Passports, but technology in general, stemming from cultural and structural characteristics inherent to the industry. Apart from socio-cultural barriers such as a general resistance to change (Ayinla & Adamu, 2018), these challenges include economic barriers, such as a particularly competitive market with strongly interdependent characteristics: low productivity and poorly integrated project planning, competitive pricing structures and narrow margins, as well as structural and organizational fragmentation resulting in supply chain complexity, amplified by poor supply chain management (Agarwal et al., 2016). Economy maturity is part of economic barriers as well, in this case the lack of a widespread acceptance of circular practices in AEC (Byers & De Wolf, 2023). And finally, adoption issues in AEC include regulatory challenges such as contracts that do not reward innovation and risk-sharing among stakeholders.

The following sections will further elaborate on relevant AEC barriers to the adoption of blockchain-based Material Passports that emerged from literature.

2.3.1.1 Market Competitiveness

The Architecture, Engineering, and Construction (AEC) sector has been characterized as uniquely competitive, due to low productivity, structural and organizational fragmentation, competitive pricing structures, narrow margins, and a multifaceted supply chain, resulting in standard modes of operation that discourage innovation and prevent the adoption of circular strategies (Luscuere, 2017; J. Li et al., 2019). This complexity encompasses all phases from commissioning to decommissioning and is compounded by the extended lifespans of buildings, which often involve various ownership and use stages (Luscuere, 2017).

Agarwal et al. (2016) and J. Li et al. (2019) identify low productivity and poorly integrated project planning as a significant barrier to the adoption of technology in AEC, blaming low levels of digitalization as underlying issue. Paper-based processes in design, procurement, and construction persists today, resulting in ineffective information exchange (J. Li et al., 2019). The lack of digitalization makes data processing and analysis difficult, critical for risk management and operational efficiency. Resulting disagreements due to varying levels of knowledge i.e. regarding modifications, often end in legal disputes (Agarwal et al., 2016).

Low productivity levels are enhanced by the AEC's structural and organizational fragmentation. Lacking economies of scale, organizations typically lack the size and capacity for research and development (R&D). Additionally, the diverse landscape of small and medium sized enterprises (SMEs) results in less knowledge exchange and more collaboration challenges (Johnson & Laepple, 2003).

Farmer (2016) further identify competitive pricing structures and narrow margins as a symptom of failure and poor performance of the AEC industry, which are closely related to poor productivity and fragmentation. As a result, profitability is too low to allow investment in critical areas like research and development and technology adoption (J. Li et al., 2019).

Supply chain complexity complements the unique characteristics of the AEC market. In fully integrated supply chains, a single organization can unilaterally decide to adopt a novel technology. Conversely, for the successful implementation of Material Passports, the construction sector demands the recognition of their potential by all stakeholders involved throughout a building's lifecycle and value chain (Agarwal et al., 2016).

Low productivity, poorly integrated project planning, industry fragmentation, slim margins, and supply chain complexity all compound each other and result in an overall lack of innovation within the industry, as a result also impeding the adoption of blockchain-based Material Passports in AEC.

2.3.1.2 Circular Economy Practices are Niche Practices (Economy Maturity)

A key barrier to the adoption of digital technology aiding the circular transition is the lack of acknowledgement for the benefits of a circular economy in AEC, evident in the niche status of material reuse (B. S. Byers & De Wolf, 2023; Luscuere, 2017; Guerra et al., 2021). Guerra et al. (2021) identify nine major circular business strategies of which the recovery and reuse of secondary materials particularly lacks an overall systemic approach. Byers & De Wolf (2023) i.e. characterize the typical Swiss building element reuse process as fragmented and driven by individual efforts.

Luscuere (2017) resonates this, stressing the current linear use of resources, with little emphasis on recycling and reuse in favour of affordability in particular, but also health and safety, and the reduction of operational carbon (Luscuere, 2017). In case materials are recovered, they are often not applied structurally due to the costs associated with evaluating and re-certifying structural components (Byers & De Wolf, 2023). Therefore, the advancement of the circular transition, including a growing technology implementation such as that of Material Passports and blockchain technology, also

necessitates a change in industry practices and standard modes of operations, substantial investment, and the exploration of novel circular economy business models (Guerra et al., 2021; J. Li et al., 2019).

2.3.1.3 Change Resistance

Change resistance emerged as another significant challenge for technology adoption in the AEC industry. Davis & Songer (2009) found that specific demographics such as profession, gender, computer understanding and experience, and awareness of past or future IT changes within their organization impacted their likelihood to resist the adoption of a new technology. Technology literacy was found to be the most important factor in the likelihood of an AEC professional to adopt a new technology, regardless their level of education or age (Davis & Songer, 2009).

In addition, construction professionals are commonly reluctant to making large upfront investments necessary for new technology implementation, albeit the foreseeable long-term benefits discussed by Ayinla & Adamu (2018). This amplified by an overwhelming amount of software continuously emerging and a lack in awareness for the benefits proposed by the new technology (Ayinla & Adamu, 2018), resulting in professionals' reluctance to take a chance. Naturally, this risk aversion towards emerging technologies impacts the adoption of all digital technologies in AEC, including blockchain-based Material Passports (BBMPs).

2.3.1.4 Conclusion

Literature on technology adoption barriers in the AEC industry revealed several key issues, including socio-cultural barriers like change resistance and a general lack of technology literacy, as well as economic barriers like poor productivity and slim margins. This highlights the urgent need for industry leaders to develop comprehensive strategies to overcome these obstacles. Going forward, understanding these obstacles will be essential to promote circular economy principles and improve sustainability in the AEC sector.

2.3.2 MP-specific Challenges

Blockchain-based Material Passports (BBMPs) face Material Passport- and blockchain-specific barriers in addition to those inherent to the AEC industry in general terms. Material Passport-barriers have been elaborated on previously and will therefore summarized shortly (*Table 2*). In addition, this chapter will discuss another important barrier: the overall technology readiness of Material Passports, a condition that blockchain technology may not be able to solve alone.

Material Passport-specific barriers that emerged from the review of literature and practice include a lack of standardization, data storage and modelling issues, lack of financial incentives, and regulatory gaps.

Table 2 Material Passport-specific BBMP-adoption barriers

Material Passport-barrier	Description
Lack of Standardization	Material passports are hindered considerably by a lack of standardized content and data formats, complicating their integration into current AEC practice (Çetin et al., 2023). However, to guarantee successful implementation, Material Passports need to be able to represent the vastly diverse landscape of building components (Luscuere, 2017).
Data Management	The wide-scale diffusion of Material Passports is significantly impacted by the lack of an efficient data storage and modelling solution, which drastically reduces its functionality (Byers & De Wolf, 2023).
Lack of Financial Incentives	Present economic mechanisms in the AEC sector don't adequately reward actors such as asset owners for their adoption of Material Passports, representing a lack of financial incentives and necessary pull factors (Byers & De Wolf, 2023).
Regulatory Gaps	The AEC industry is further disincentivized to fully integrate Material Passports due to a lack of supportive regulation and legal frameworks, which fail to deliver the required push factors (Azcarate-Aguerre et al., 2022).

2.3.2.1 Technology Readiness

Material Passports as a technology are not as developed as they need be for wide-scale diffusion in AEC practice where they could contribute to facilitating a circular built environment. Most Material Passport solutions aren't sufficiently sophisticated yet and mainly cater to "early adopters" (Rogers, 2003). The Technology Readiness Levels as described by the European Commission (2013), based on (Mankins, 1995a), as well as their relation to the technology diffusion theory by Rogers (2003) help to assess their maturity and readiness for wider adoption.

Technology Readiness Levels (TRLs), which range from "basic principles observed" (TRL 1) to "actual system proven in operational environments" (TRL 9), offer a framework for evaluating a technology's maturity (European Commission, 2013; Mankins, 1995b). In parallel, the Innovation Diffusion Theory published by Rogers (2003) explains how innovations are adopted in society. It shows how different "adopters" embrace innovations according to their character attributes, such as how prone they are to take risk, their innovation willingness, and their access to financial resources.

Material Passport solutions generally fall within Technology Readiness Level 5-7: "system prototype demonstration in operational environment" (European Commission, 2013). As an example, with their Material Passport, Madaster essentially provide building-level Life Cycle Assessments (LCAs) but fall short in delivering the whole range of potential value propositions of Material Passports. This aligns with Rogers (2003), according to which Material Passports are moving from an early adoption phase, in which so-called "innovators" experiment with them, to a broader audience.

In the case of Material Passports this reveals the complexity in the interrelation of the various mechanisms that affect the adoption of a technology: even if technical practicalities such as standardization and data storage and modelling were solved, Material Passports could still fail. Because as much as they are considered to be circular economy enablers, they are also dependent on a growing awareness within the AEC community and the increased adoption of circular practices in general. The more material reuse and design for deconstruction etc. become the norm, the more Material Passports become inevitable for construction professionals.

2.3.2.2 Summary MP-specific Challenges

The integration of blockchain-based Material Passport into AEC industry practice is restricted by several important barriers specific to Material Passports. These barriers range from a lack of standardization and data management issues to inadequate financial incentives and gaps in regulatory frameworks. Furthermore, the notion of technology readiness surfaces as a significant concern, suggesting that although Material Passports have potential to promote a circular economy in the construction industry, their current state of development might not allow for sector-wide adoption. The adoption of blockchain-based Material Passports in addition also faces blockchain-specific adoption barriers, which will be discussed in the following chapter.

2.3.3 Blockchain-specific Challenges

Barriers to the adoption of blockchain technology in the construction sector will be explored in the following sections as part of blockchain-based Material Passport-barriers. J. Li et al. (2019) list the following challenges related to the implementation of blockchain in the construction industry: authentication of data, bandwidth and connectivity, coding of smart contracts, energy consumption, exchange rate volatility, interoperability, legal challenges, malicious attacks, readiness for adoption, resistance to change, skills, and the technology state of the industry. These barriers will be briefly summarized and elaborated on for more context.

2.3.3.1 Lack of Financial Incentives

High implementation cost, particularly when integrating BIM and IoT devices with blockchain for the optimisation of construction management processes, are discussed by J. Li et al. (2019) as part of the adoption barriers of blockchain technology in AEC. In addition to the costs for setting up the blockchain infrastructure, significant costs and delays could be introduced because IoT-enabled devices would be required for every building system or component (Heiskanen, 2017; J. Li et al., 2019). Furthermore, high transaction fees of blockchains, specifically proof-of-work consensus mechanisms, make large-scale data storage impracticable (J. Li et al., 2019), restricting blockchains to recording transactions rather than storing information. However, large traffic volumes of transactions in the case of large datasets could likewise drive up operational cost.

In addition, Hunhevicz et al. (2023) highlight that companies currently benefit from information asymmetry and therefore are disincentivized to share data in public networks.

And lastly, J. Li et al. (2019) refer to the extreme volatility of cryptocurrencies as a problem for the often-praised potential of blockchain technology to provide financial incentive systems to the construction industry.

2.3.3.2 Regulatory Frameworks

Regulatory barriers to the adoption of blockchain technology in AEC include legal concepts of property ownership and private law agreements such as the industry's dependence on legally binding contracts and its inability to integrate smart contracts. Azcarate-Aguerre et al. (2022) i.e. describe the dilemma of property ownership confinements, making novel business models such as Products-as-a-Service (PaaS) very challenging to realize. Further, immutable ledgers prove difficult to adopt, as their fundamental property 'immutability' was ruled incompatible with EU privacy policy and the 'right to be forgotten' (Kranenborg, 2015).

Apart from legislation actively impeding the adoption of blockchain in AEC, the prevalent absence of clear laws and governance, especially regarding cryptocurrencies, also prohibits blockchain integration (J. Li et al., 2019). This means that in the AEC industry, regulatory changes are required to strike a balance between incentivizing innovation and establishing operational and legal boundaries.

2.3.3.3 Technical Practicalities

Barriers related to technological aspects of blockchain technology are by far the most discussed adoption challenges of blockchain technology in the AEC sector. *Table 2* provides an overview of the most important ones, including a brief description.

Table 3 Blockchain-specific adoption barriers: technical practicalities

Technical Practicality	Description
Coding of smart contracts	A faultless and farsighted code is essential for the long-term functionality of smart contracts, which are intended to trigger transactions automatically over decades. Errors could potentially have grave consequences for the involved parties because of their permanent nature, especially considering the longevity of projects in AEC (J. Li et al., 2019).
Data authenticity	As well as a blockchain network may be designed, it is still dependent on data input, meaning data-entries need to be authenticated to avoid fraud or malfunction. And because blockchain systems need consensus before modifications can be performed, demanding time and effort, they frequently lack scalability and flexibility (J. Li et al., 2019), amplified if inaccurate or fraudulent data is introduced to the system.
Data security	Although praised for its tamper-proofness, blockchain networks are not immune to cyberattacks that may result in the loss of data or tokens, jeopardizing integrated systems that put trust in data integrity and confidentiality (J. Li et al., 2019).
Data storage	Blockchain technology is dependent on a large network of servers, each of which need continuous internet connection to operate (J. Li et al., 2019). Designed to maximize decentralization and eliminate “single points of failure”, a careful design is still needed to limit its vulnerability (Hunhevicz et al., 2023). On a practical note, if access to an off-chain database such as IPFS was lost, the fundamental properties of blockchain would prevent the simple restoration of access to the datasets (Hunhevicz et al., 2023). Additionally, proof-of-work consensus mechanisms are redundant by design, therefore demand large data storage capacities, consuming a lot of resources (J. Li et al., 2019). This can limit throughput and transaction latency (J. Li et al., 2019).
Interoperability	Ensuring the transfer of data between different platforms and systems (hardware/software) is essential for the construction industry, demanding this communication with databases and digital technologies from the blockchain architecture (Wang et al., 2017).
System integrity	Blockchains are vulnerable to the emergence of network forks if new apps or upgrades are added to the application layer and users cannot agree which version to support. This can result in two parallel ecosystems, both deriving from the previous chain of blocks. These divisions have the potential to compromise the system's integrity, essentially discouraging stakeholders who depend on the stability of these systems (J. Li et al., 2019).

2.3.3.4 Technology Readiness

The technology readiness of blockchain poses a key barrier to the adoption of blockchain-based Material Passports into AEC practice, especially as this sector has yet to embrace digital transformation. Recent publications make clear how early the technology still is in its development and industry-wide dissemination (Hunhevicz et al., 2023; J. Li et al., 2019). Blockchain technology is still very dependent on the development of supporting regulatory frameworks, an example being Decentralized Architectural Organizations (DAOs). At the same time, blockchain applications are struggling to enter the AEC industry, compared to more technologically sophisticated industries,

because of the absence of a foundation of digitalized cooperation, information sharing, and general openness to digital technology advancements (J. Li et al., 2019).

2.3.3.5 Environmental Impact

Blockchain's substantial energy consumption, especially that of the computing-intensive proof-of-work consensus mechanisms, poses a unique barrier for the adoption of a technology that, at least in the case of Material Passports, is intended to promote environmentally sustainable practices. Although the continuous advancement of blockchain-design options and revisions of consensus mechanisms aim to also mitigate energy requirements of blockchain, J. Li et al. (2019) suggest that this issue prevails and needs further attention.

2.3.3.6 Lack of Knowledge

Another barrier for the adoption of blockchain technology mentioned by J. Li et al. (2019) is a lack of knowledge about novel digital technologies, specifically the potential benefits of blockchain for construction processes, among many professionals in the conservative construction industry. Also, there is an apparent scarcity of appropriately qualified experts with the necessary skills to build and operate blockchain infrastructures in AEC, what J. Li et al. (2019) relate to the relative novelty of the technology in the industry.

2.3.3.7 Change Resistance

The considerable modifications to processes across all organizational levels demanded by blockchain technology challenges an industry that has historically been reluctant to change. This previously described barrier summarizes practitioners' reluctance to divert from business as usual. This opposition may keep businesses from reaping the benefits blockchain technology has to offer, including improved security, efficiency, and transparency (J. Li et al., 2019).

2.3.3.8 Lack of Trust & General Scepticism

Lastly, the widespread mistrust and lack of confidence in blockchain technology, as described by J. Li et al. (2019), is characterized by several factors: potential users' association of blockchain with unlawful activities, such as the dark net, and the fear of job displacement due to the inherent capacity of blockchain to automate processes. Also, various challenges to ensuring the confidentiality and privacy of transaction data are mentioned, especially in public blockchains. And despite its fundamental properties, blockchain is eventually still reliant on users' honesty (J. Li et al., 2019).

2.3.3.9 Summary Blockchain-specific Challenges

This review of the literature on adoption barriers of blockchain technology in the AEC industry revealed many important challenges. They include the interplay of financial restrictions resulting from high implementation costs and a scarcity of qualified blockchain-specialists in AEC, and a lack of regulatory frameworks supporting its industry-wide implementation. Further, unresolved issues of technical aspects such as the careful coding of smart contracts, high energy consumption, as well as systemic issues like the general questioning of persistent procurement and delivery practices qualify as significant barriers. And lastly, the AEC industry must overcome a lack of knowledge about blockchain to reduce resistance to change and a general lack of trust in the technology.

2.4 Summary Theoretical Background

To provide a strong theoretical background as basis for the empirical research in this study, this literature and practice review helps grasp the extensive landscape of blockchain-based Material Passport (BBMP)-integration into AEC practice. Recent academic literature, institutional reports, and commercially offered material was reviewed to synthesize information on the fundamental concepts:

Material Passports, blockchain technology in AEC, and the unique environment of the construction sector.

Material Passports (MPs) appear to have tremendous promise for facilitating a circular transition in the AEC industry. But the review of the current body of literature reveals some unresolved issues which prevent their widespread adoption. These include both adoption barriers that technological innovations in AEC face in general, as well as barriers specific to the adoption of Material Passports. *Table 4* provides the outcome of this literature review in respect to Material Passport-adoption barriers.

AEC-general barriers include the overall unique market-competitiveness of the construction sector characterized by industry fragmentation, low productivity, slim margins, and complex supply chains, that are compounded by the sectors traditional practices and general resistance to embracing new digital technologies.

Literature also revealed barriers specific to Material Passports, which include definition inconsistencies, contributing to the lack of content standardization. Additionally, technological obstacles such as inadequate data management practices are significant as they have an impact on how Material Passports are integrated into current AEC practice and potentially limit their potential. Furthermore, the interaction of economic and legal obstacles, including a lack of financial incentives and the absence of supporting regulatory frameworks, emerge as an important barrier for industry-wide Material Passport adoption.

Table 4 Material Passport-adoption barriers, derived from literature

Category	Barrier
AEC-general barriers	Market-competitiveness
	CE practices remain niche practices (economy maturity)
	Change resistance
	Lack of digitalization
MP-specific barriers	Lack of standardization
	Data storage & modelling
	Lack of financial incentives
	Regulatory & legislative gaps
	Technology readiness

By improving data quality, transparency, and transaction security, academia suggests that blockchain technology offers a viable solution to these unresolved issues of Material Passports. In addition to optimizing Material Passports' operating capabilities and changing the industry's modus operandi, blockchain could provide new financial incentives when integrated with Material Passports. Despite these benefits, there haven't been many attempts in the AEC sector to integrate Material Passports and blockchain technology.

As another important component to the potential adoption barriers of blockchain-based Material Passports, the literature review further revealed a list of barriers for the adoption of blockchain alone, including financial, regulatory, and technical challenges. The outcomes of the literature review in respect to blockchain-specific challenges are presented in *Table 5*:

Table 5 Blockchain technology-adoption barriers in AEC, derived from literature

Category	Barrier
Blockchain-specific barriers	Lack of financial incentives
	Regulatory frameworks
	Technical practicalities
	Technology readiness
	Environmental impact
	Lack of knowledge
	Change resistance
	Lack of trust & general scepticism

The identification of these challenges emphasizes the necessity of conducting semi-structured interviews with professionals and academics in the field to gather insights on how practice is applying Material Passports, as well as what challenges practitioners associate with Material Passport applications in contrast to academia. The expert interviews may identify new adoption barriers or provide more context to those that have previously been identified in literature.

The review of practice highlights the focus Digital Product Passport- or Material Passport-providers put on the significance of financial benefits that lie in the adoption of their solutions, which are frequently promoted more for their potential to improve trust, brand image, and regulatory compliance than for sustainability reasons. This indicates that the industry is motivated by possible financial consequences of non-compliance and a fear of losing customer loyalty, extrinsic motives, rather than intrinsic ones. To advance the theoretical insights from literature and provide more context to the observations from web search, a comparative case-study analysis will be conducted as final method of data collection.

3 Methodology

This research is grounded in a literature and practice review exploring its underlying concepts. The following chapter will outline the chosen methodology, including research design and system of methods.

3.1 Research Design

The fact that blockchain-based Material Passports are not yet adopted in practice suggests a qualitative research design. Nevertheless, methods are combined to balance out the strengths and weaknesses of each qualitative method and to synthesize and validate findings in a way that is not possible with a single research method (Blaikie & Priest, 2019; Creswell John W. & Clark Vicki L. Plano, 2007).

The objective of this research is diverse, including the exploration and description of blockchain-based Material Passport opportunities, as well as the thorough understanding of their adoption barriers into AEC industry practice.

This research is predominantly of descriptive nature as suggested by the main research question (Blaikie & Priest, 2019), a ‘what’ question, and therefore will result in a list of blockchain-based Material Passport opportunities in form of use cases and a list of barriers for the integration of blockchain-based Material Passport into practice. By including this range of objectives and highlighting these barriers, this research aims to actively promote transformative change in AEC. In line with the research objectives, the sub questions are essential to establishing a clear structure and narrate the course of research. They first facilitate a descriptive inquiry of known barriers to the adoption of the two technologies Material Passports and blockchain technology, then an on-case investigation of the opportunities and barriers of their integration.

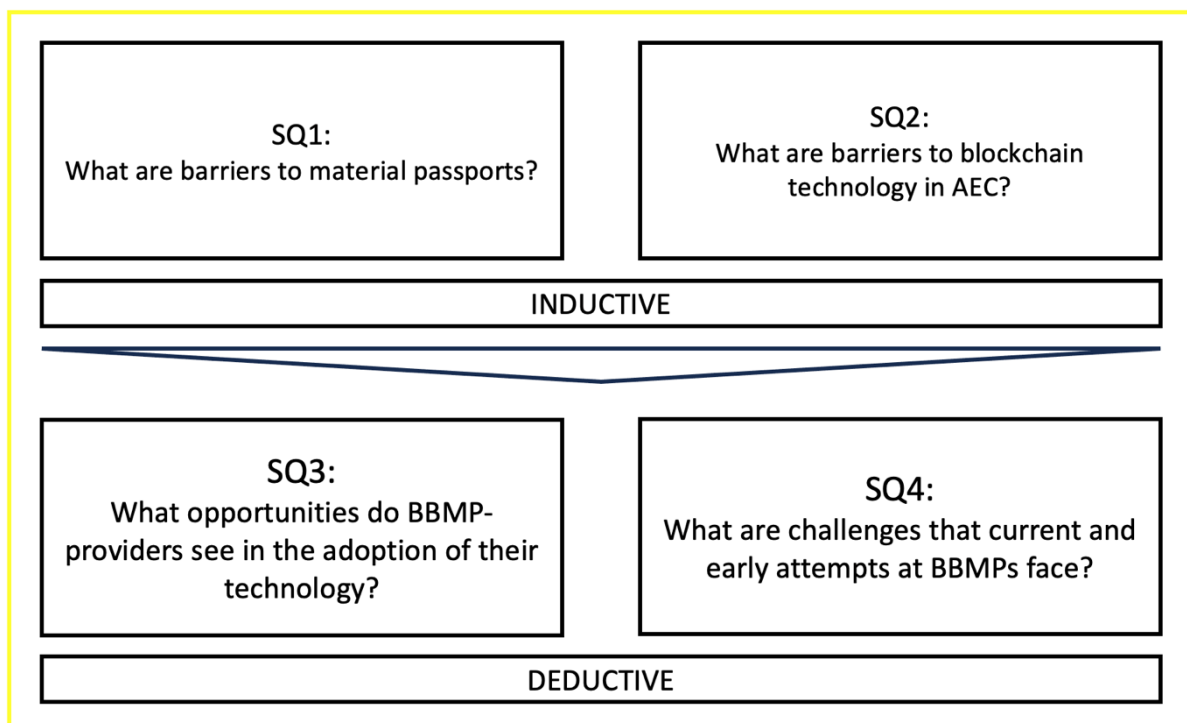


Figure 7 Research design - logics of inquiry (author)

The primary logic of inquiry is inductive, juxtaposed by a deductive logic to enhance the research findings (Figure 7).

Sub questions one and two apply inductive logic of inquiry to address the subjects of investigation (Blaikie & Priest, 2019). According to Blaikie & Priest (2019), it involves gathering data first, then drawing conclusions and generalizations from it. In the context of social research, its focus is on illustrating social characteristics and identifying patterns within human behaviour. The mechanisms underlying technology adoption in the AEC sector are too complex to anticipate in advance. Therefore, the inductive logic of inquiry will be helpful in shedding light on them.

In contrast, deductive logic of inquiry is a top-down approach, as described by Blaikie & Priest (2019), formulating a theoretical argument first, and the drawing conclusions from collecting appropriate data. If the findings are consistent with the hypothesis, they support its continued application, otherwise the hypothesis needs to be adjusted or rejected (Blaikie & Priest, 2019). Sub questions three and four follow a deductive methodological approach, building on findings and conclusions from sub question one and two.

3.2 System of Methods

The following section will outline the methods applied for data collection and data analysis. Empirical research is split in two distinct phases, that each represent different qualitative research methods as depicted in *Figure 8*. Phase one consists of conducting semi-structured interviews with experts relevant to the research. It aims at answering sub questions one and two. Phase two, following an analysis and mapping of findings from phase one, consists of a comparative case-study analysis. Its objective is to answer sub questions three and four of this research. The findings from both phases of data collection aim to provide the answer to the main research question. Both methods, including scoping, and assessment framework and coding, will be individually explained in the following sections.

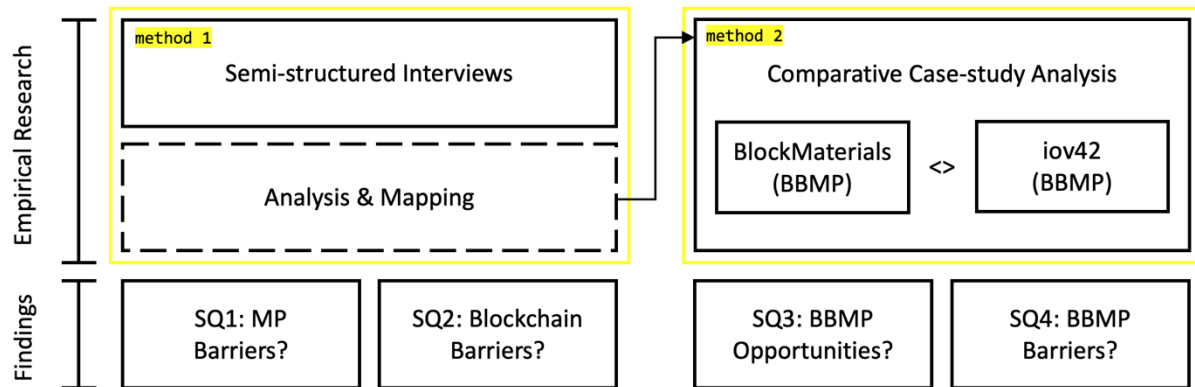


Figure 8 Research design methods

3.2.1 Method 1: Semi-structured Interviews

Literature on unresolved issues for Material Passports is fragmented, emphasizing the need for a comprehensive and qualitative study. Therefore, semi-structured interviews were carried out during phase one of empirical research. Although interactive, an interview has a defined objective, providing a deeper knowledge of opinions and experiences of experts and professionals (Bryman, 2016). By engaging a wide variety of stakeholders, they can gather information on how practice is applying Material Passports and how practitioners view possible applications for blockchain-based Material Passports (BBMPs). Further, expert interviews help to identify additional adoption barriers and put those previously identified in literature into perspective.

The interview questions were be centred around the following subjects (*Appendix B*):

- Interviewee background
- Material Passports and their use cases
- Blockchain technology and Material Passport-integration
- Possible blockchain-based Material Passport adoption enablers
- Future recommendations

The richness and depth of the research findings is influenced by the quantity and quality of interview participants. The study targeted a wide variety of participants from academia and practice based on their direct participation with or competence in the fundamental concepts of this research, ensuring authenticity and applicability of the gathered information. As a result, every interview was customized to the distinct background of the interviewee.

Due to rates of responses, eight participants were interviewed as shown in *Table 6*. The participants have been assigned codes to ensure anonymity.

Table 6 Interviewees

Code	Type of Organization	Role
LF.1.LA	Law firm	Legal adviser
MP.1.PM	MP provider	Employee
MP.1.PL	MP provider	Employee
MP.1.D	MP provider	Leader
MP.1.MD	MP provider	Leader
RI.1.R	Research institute	Researcher
RI.2.R	Research institute	Researcher
RI.3.AP	Research institute	Researcher

As described in the methods section, participants were identified using a combination of purposive sampling, critical case-, snowball-, and opportunistic sampling (Bryman, 2016). Due to the novelty of the field, key stakeholders proved to be market leaders and legal experts. Unfortunately, due to a lack of responses, only one Material Passport-provider was represented in the interviews. Subsequently, researchers were selected to add more diverse perspectives to the collected data set.

3.2.1.1 Interview Contents and Line of Questioning

Designed to follow a semi-structured format, the interviews followed interview rules while maintaining flexibility in the interaction with the interviewee, leaving freedom to explore possible themes they might find important. As can be seen in *Appendix B*, the interviews first set up a basis for discussion by defining the underlying concepts of the research and identifying possible use cases for Material Passports, as well as their integration with blockchain technology. Depending on the interviewee background, the interviews then dove deeper into either one of the aspects: Material Passports and their specific opportunities and challenges from the perspective of the interviewee on the one hand, and blockchain technology and its potential for AEC and Material Passports on the other hand, as well as the opportunities and challenges faced by the integration of both technologies.

3.2.1.2 Assessment Framework and Coding

The PESTLE framework of analysis served as basis for data analysis, specifically for the structured identification and categorization of all relevant blockchain-based Material Passport adoption barriers. The abbreviation PESLITE stands for the strategic evaluation of the impact of political, economic, social, technological, legal, and environmental factors on an object of analysis. Widely established in management research and practice as a diagnostic tool to detect external factors impacting

operational processes, strategy, and business decisions, researchers have adapted it in various ways i.e. to evaluate the impact of barriers and solutions on the development of sustainable buildings (Dalirazar & Sabzi, 2023), to address the barriers influencing solar home system provision in refugee camps in Rwanda (Thomas et al., 2021), or identify external risks for construction projects in general (Trivedi et al., 2016).

The framework was in this case used to identify and categorize barriers in a structured manner.

P	E	S	T	L	E
Political	Economical	Social	Technological	Legal	Environmental
Political variables that affect how governments may affect sectors and organizational revenue structures, including tax policies, fiscal and trade policies, as well as political stability and its impact on the economic environment.	Economic factors that affect supply and demand dynamics including inflation, interest rates, exchange rates, and patterns of economic growth, having a direct influence on investment behaviour and purchasing power.	Social factors such as cultural barriers, demographics, and health considerations impact human behaviour and subsequently project success.	Technological development dynamics yield considerable impact on industrial operations and market dynamics due to factors such as technology readiness, automation, technology literacy, the overall level of digitalization, and cyber security.	Legal considerations include how regulatory frameworks actively or passively affect the adoption of systems, such as taxation and trade laws, and regulation including labour rules and safety standards.	Environmental circumstances significantly impact corporate operations and project outcomes such as climate change, weather and geographic position, pollution, as well as policies and sustainability regulation.

Figure 9 PESTLE analysis framework (adopted from CIPD (2024) and Trivedi et al. (2016))

The interviews were coded using categories that emerged from mapping the literature output onto the PESTLE framework. These codes, so-called closed codes, are depicted in Table 7. Further categories (barriers) that weren't discussed in literature emerged from the interviews, added to the list as 'open' codes and subsequently allocated to the appropriate PESTLE-category.

To meet the structure of the underlying concepts of this research, the coding structure was divided into Material Passport-specific barriers, barriers specific to blockchain technology, as well as general barriers regarding technology adoption in the AEC industry.

Underlying concepts such as the definition and use cases of Material Passports and blockchain technology were coded to improve the general understanding of the object of analysis. However, they are not included in the research findings.

Table 7 Coding structure semi-structured interviews

MP-inherent barriers	Closed/open
Lack of financial incentives	Closed
Regulatory frameworks	Closed
Technical practicalities	Closed
Technology readiness	Closed
Inadequate information provision	Open
Lack of knowledge (CE & MPs)	Open
Blockchain-inherent barriers	Closed/open
Knowledge-barrier	Closed
Regulatory frameworks	Closed
Technical practicalities	Closed
Technology readiness	Closed

Environmental impact	Closed
Lack of trust & general scepticism	Closed
AEC general barriers	Closed/open
Change resistance	Closed
Industry fragmentation	Closed
Lack of digitalization & technology literacy	Closed
Market-competitiveness	Closed
Chicken & egg problem	Open
Economic-political context	Open

To ensure a thorough extraction of findings from the interviews, quotes were coded if they literally mentioned certain terms included in the names of codes or their subcodes as well as if they captured the meaning and context of a code without literally stating the code name. This way, significant information was not missed because of a lack of precise language.

Figure 10 depicts the closed and open codes of the semi-structured interviews mapped on the PESTLE analysis framework. A detailed elaboration will follow with the presentation of the findings. Open codes are highlighted in red, revealing gaps in the academic discourse of the barriers for the adoption of blockchain-based Material Passports.

P	E	S	T	L	E
Political	Economical	Social	Technological	Legal	Environmental
- Adverse economic-political context	- Chicken & egg problem - Industry fragmentation (AEC-industry) - Lack of financial incentives (MPs) - Market-competitiveness (AEC-industry)	- Lack of trust & general scepticism (blockchain) - Change resistance (AEC-industry)	- Inadequate information provision (MPs) - Lack of knowledge (CE & MPs) - Lack of knowledge (blockchain) - Lack of digitalization & technology literacy - Technical practicalities (MPs) - Technical practicalities (blockchain) - Technology readiness (MPs) - Technology readiness (blockchain)	- Regulatory frameworks (MPs) - Regulatory frameworks (blockchain)	- Environmental impact (blockchain)

Figure 10 Semi-structured interview codes closed (black) & open (red) mapped on PESTLE analysis framework (author, 2024)

3.2.2 Method 2: Comparative Case-study Analysis

The concepts derived from the desk research and semi-structured interviews were followed up by a comparative case-study analysis. Findings from semi-structured interviews were synthesized to develop a preliminary list of blockchain-based Material Passport (BBMP) adoption barriers, which were then used as coding schema in the analysis of early attempts at blockchain-based Material Passports in practice.

Throughout literature, various definitions of “case-study” exist. Blaikie & Priest (2019) describe them as a wide category of research methods that share the goal of concentrating attention on a single instance. They provide an opportunity to examine a contemporary problem in its real-life setting (Blaikie & Priest, 2019).

Given the early stage of technology development and commercialisation of BBMP-projects, it is precisely the right moment to study their use cases to identify opportunities and barriers they experience. The comparison of two such case studies allows highlighting common patterns, differences, and complexities.

Blaikie & Priest (2019) also outline that case-studies are suitable for postgraduate research as they provide a reasonable scope to be able to concentrate on one element of a problem within a limited timeframe. This is because a case study can handle a wide range of variables of interest versus a limited number of available data points (Blaikie & Priest, 2019). Consequently, this method aligns seamlessly with the research objectives.

Among the few options available, cases included publicly promoted cases by the companies BlockMaterials and iov42. 'The company' is adopted as the unit of analysis, with a particular emphasis on the point of view of stakeholders within each organization. After analysing and coding the conducted interviews per case, they are triangulated with online publications of various kinds to map the final opportunities and barriers.

3.2.2.1 Case-study Selection

The two cases selected for the comparative case-study analysis were based on two main conditions as the primary selection criteria. The first criteria included that an organization provided a product passport that is applied in AEC. Due to the scarcity of mature Material Passport solutions, this wide scope was adopted to not only include solutions solely targeting the AEC sector, but also Digital Product Passports that, in specific use cases, document products for the construction industry. *Table 8* presents all possibly eligible use cases that were included in the longlist: Material passports including the BAMB project and its prototype of a Material Passport-platform (BAMB Buildings as Material Banks, 2016), BlockMaterials using the CIRDAX software by reusematerials.nl (BlockMaterials, n.d.), Concular (Concular GmbH, 2024b), possibly Home.Earth (Home.Earth, 2023), and the previously mentioned Madaster Foundation (Madaster Services BV, 2024), and Circularise (Circularise, 2023), and iov42 (iov42, 2024b) as Digital Product Passports with AEC-related applications.

As second selection criteria, the case studies had to have blockchain technology integrated with their passport solution in some form, from the simple hashing of unique identifiers assigned to Material Passports on a blockchain ledger to the full-stack blockchain integration across the whole system architecture of a passport platform. Based on web search, the longlist was reduced to a shortlist of four cases (BlockMaterials, Circularise, iov42, and Madaster). However, due to unclarity about the blockchain integration in some cases, the selection process further necessitated scoping interviews. BlockMaterials and iov42 emerged as the two businesses matching all requirements and were subsequently selected as the case studies for this research due to non-responses (Circularise) and disqualifications (Madaster).

Table 8 Selection process case studies

Selection criteria			Scoping (eligible cases)
1	Product passport	MP (AEC only)	BAMB2020.eu
			BlockMaterials (CIRDAX/reusematerials.nl)
			Concular
		DPP (use case in AEC)	Home.Earth?
			Madaster
			Circularise
2	Blockchain integration	MP	BlockMaterials (CIRDAX/reusematerials.nl)
			Madaster?
		DPP	Circularise?
			iov42
3	Final selection: BBMP		BlockMaterials (CIRDAX/reusematerials.nl)
			iov42

Participants were identified using a combination of purposive, critical case-, snowball-, and opportunistic sampling (Bryman, 2016), the latter playing an important role due to limited responses.

It was crucial to gather different perspectives of experts from within the organizations studied in the case studies. Therefore, the following roles were targeted for interviews:

- Participants with insight into the strategic positioning of the company's operations
- Participants with a sound understanding of the technical details and practical experience of integrating their passport solution.

3.2.2.2 Case-study 1 - BlockMaterials

As indicated in Table 9, a total of three representatives were interviewed for case-study one, all of which were personally involved with the case. The participants were assigned codes to ensure anonymity. As members of executive management, participants 01_BM and 03_BM were able to provide strategic insights into business operations, coordinating their organizations objectives with funding and political support, as well as outlining research projects. Participant 02_BM had experience in integrating and issuing the organizations BBMP-solution. Together, the interviewees offer valuable insights from both technical and strategic perspectives.

Table 9 Case-study 1 - interviews

Code	Type of Organization	Role
01_BM	BlockMaterials	Leader
02_BM	BlockMaterials	Employee
03_BM	BlockMaterials	Leader

The results from these interviews were triangulated using the following data points:

Table 10 Case-study 1 - data triangulation

Code	Type of data
BlockMaterials (2024)	Website

De Simplist (2022)	Interview
Simon Duindam, 2022	Book

3.2.2.3 Case-study 2 – iov42

For case-study 2, iov42, two representatives were interviewed (*Table 11*). Participants were assigned codes to ensure anonymity. Being directly involved with the case, both participants have first-hand experience with their BBMP-solution. As business executive with responsibility for strategic market positioning, interviewee 01_iov42 was able to offer insights into business objectives and overall operational aspects. In contrast, interviewee 02_iov42, responsible for the product development and maintenance, was able to provide information on technical and practical aspects of implementing their passport-solution. This way, case 2 also provides thorough insight to strategic and technical perspectives.

Table 11 Case-study 2 - interviews

Code	Type of Organization	Role
01_iov42	iov42	Leader
02_iov42	iov42	Employee

The results from these interviews were triangulated using the following data points:

Table 12 Case-study 2 - data triangulation

Code	Type of data
iov42 (2024)	Website
Interu by iov42 (n.d.)	Website
iov42 (2024)	Blog post
iov42 (2024)	Blog post
iov42 (2024)	Blog post
iov42 (2024)	Blog post
iov42 (2022)	YouTube tutorial – Timber Chain
Innovation zero (2023)	Conference presentation
Technology connected (2024)	Interview (technology industry association Wales)

3.2.2.4 Comparative Analysis and Coding

The case-study interviews were coded using categories that were deducted from the previous method. As indicated in *Table 13*, they represent the codes used for the semi-structured interviews, merging Material Passport-inherent and blockchain-inherent barriers to blockchain-based Material Passport barriers. This is coherent as the implications discussed in these interviews naturally implied their impact on the respective BBMP-solution. ‘Open’ codes didn’t emerge because all discussed barriers had been mentioned before.

The coding structure was divided in respect to answering sub questions three and four: blockchain-based Material Passport-specific adoption barriers, and general barriers regarding technology adoption in the AEC industry. Further, codes were assigned for blockchain-based Material Passport opportunities, but also case descriptions and the underlying concepts of Material Passports and blockchain technology, which served as basis for the case descriptions.

Table 13 Coding structure Case-study interviews

BBMP-inherent barriers	Open/closed
Environmental impact (blockchain)	Open
Inadequate information provision (BBMPs)	Open
Knowledge-barriers (CE & MPs/blockchain)	Open
Lack of financial incentives (BBMPs)	Open
Lack of trust & general scepticism (blockchain)	Open
Regulatory frameworks (BBMPs)	Open
Technical practicalities (BBMPs)	Open
Technology readiness (BBMPs)	Open
AEC general barriers	Open/closed
Change resistance	Open
Chicken & egg problem	Open
Economic-political context	Open
Industry fragmentation	Open
Lack of digitalization & technology literacy	Open
Market-competitiveness	Open

Same as the semi-structured interviews, the quotes from the case-study interviews were coded both if codes were literally mentioned or if they captured the meaning and context of a code to ensure a thorough extraction of findings from the interviews.

The combined blockchain-based Material Passport-barriers, as subsumed from the semi-structured interview findings and mapped across the PESTLE framework of analysis, are depicted in *Figure 11*:

P	E	S	T	L	E
Political	Economical	Social	Technological	Legal	Environmental
- Economic-political context	- Chicken & egg problem - Industry fragmentation (AEC-industry) - Lack of financial incentives (BBMPs) - Market-competitiveness (AEC-industry)	- Lack of trust & general scepticism (blockchain) - Change resistance (AEC-industry)	- Inadequate information provision (BBMPs) - Lack of knowledge (CE & MPs/blockchain) - Lack of digitalization & technology literacy - Technical practicalities (BBMPs) - Technology readiness (BBMPs)	- Regulatory frameworks (BBMPs)	- Environmental impact (blockchain)

Figure 11 Case-study interview codes mapped on PESTLE analysis framework

4 Findings

The following chapter will present the findings of the empirical research conducted throughout this research, aiming to identify the opportunities of integrating blockchain-based Material Passports (BBMPs) in the architecture, engineering, and construction (AEC) industry as well as their respective adoption barriers. The chapter is structured around the two methods semi-structured interviews and a comparative case-study analysis, which are guided by the four sub questions “*What are barriers to Material Passports?*”, “*What are barriers to blockchain technology in AEC?*”, “*What opportunities do BBMP-providers see in the adoption of their technology?*”, and “*What are challenges that current and early attempts at BBMPs face?*”.

4.1 Findings from Semi-structured Interviews

Answering the first two sub questions, the semi-structured interviews build on the theoretical insights about Material Passport- and blockchain technology-adoption barriers in AEC presented in chapter 2 *Theoretical Background*.

The following section will present the findings of phase one of empirical research by first presenting general barriers specific to AEC characteristics as mapped on the PESTLE analysis framework, followed by MP-specific adoption barriers, and then blockchain-specific barriers.

4.1.1 AEC-general Barriers

The following paragraphs will briefly describe the most significant ones according to quantity of mentioning: adverse economic-political context, the relationship of regulation and market incentive mechanisms, AEC industry fragmentation, overall market competitiveness, change resistance, and an overall lack of digitalization and technology literacy. Quotes in these sections come directly from participants in the study. These can be accessed in *Appendix E*, which visualizes how findings were derived from interview responses by summarizing AEC-general barriers, their categorization in the PESTLE analysis framework, as well as detailed descriptions and corresponding evidence from the semi-structured interviews.

4.1.1.1 *Adverse economic-political context – open*

Adverse economic-political context was mentioned five times throughout the interviews. They describe economic effects of political environments such as the level of economy maturity, information accessibility in a unique national context, and the clash of proposed decentralized systems and totalitarian regimes.

The question of economy maturity was brought forward by one interviewee and seems to be an important consideration as the adoption of a new technology is dependent on whether the economic environment is developed enough to integrate the technology. In part, this has to do with the general level of digitalization, as elaborated on later. However, in general terms, one blockchain in AEC-researcher summarized the issue like this: “So it's also a matter of ... what are people worried about, right? ... the circular economy is a first world problem in my opinion...” (RI.3.AP, 2024).

Economy maturity leads to the next element of economic-political context, pointed out by a Material Passport provider: technologies such as Material Passports and blockchain are often developed based on the economic and technological standard of a specific Western European context. However, most countries don't have an accessible information landscape as a foundation, as i.e. the Netherlands does. Most countries suffer from “data starvation”, which strips Material Passports of their basis (MP.1.PM, 2024).

And lastly, proposing decentralized systems such as blockchain or Web3-technologies might fundamentally contest the political system of the country in which the technology is supposed to be

adopted, such as totalitarian regimes. The blockchain-researcher specifically names China as a country in which blockchain is discussed in different light than in Europe (RI.3.AP, 2024).

Therefore, the economic-political context can create important challenges for the adoption of digital technologies at large and highlight the complicated interaction between technology and each country's unique conditions. This relationship of regulatory environment and economic landscape is discussed further in the following section.

4.1.1.2 Chicken & egg problem – open

Although actively named only a few times, the dilemma of whether to favour regulation over market incentives to help a technology in its adoption or vice versa ran like a red thread through all the interviews. The blockchain-researcher for example poses the question of how demand for a technology can be created and adds "...a lot of times, for example, states create markets or ... conditions create markets..." (RI.3.AP, 2024). On one hand, most participants called for regulation when being asked about how to overcome an adoption barrier. Further, another researcher in the field described how regulation drives development, but at the same time questioned the effectiveness thereof by referring to governments mandating the use of BIM, which resulted in a statistical increase in BIM usage rates, however not at the intended level of maturity (RI.1.R, 2024). Thus, while acknowledging the innovation-driving power of a top-down approach, participants are also weary of their effectiveness. On the other hand, some participants would prefer a bottom-up approach of incentive systems and the demand for a technology naturally growing by itself, most poignantly represented by one researcher: "...as little as possible should be regulated. ... I'm convinced that top-down approaches never work..." (RI.2.R, 2024).

This recurring theme of either prioritizing the centralized approach of regulation or the decentralized approach of market incentives resonated throughout all interviews, however without reaching a consensus.

4.1.1.3 Industry fragmentation (AEC-sector) – closed

Another challenge mentioned in the semi-structured interviews was the characteristic of a very fragmented AEC industry, both by a Material Passport provider as well as a researcher. The reason for industry fragmentation being a problem for technology adoption is the necessity for complex coordination between multiple small parties resulting in slower innovation diffusion. At the same time, the fragmentation of the construction industry is characterized by a lot of Small- and Medium-sized Enterprises (SMEs) that struggle with limited resources for technology investments, visible in the slim margins that these parties operate on (RI.3.AP, 2024).

4.1.1.4 Market-competitiveness (AEC-sector) – closed

Market-competitiveness emerged as a significant barrier from the interviews with both AEC practitioners and researchers. As already indicated earlier, a unique characteristic of the construction industry resonated by multiple participants was that it operates on slim margins, estimated by one researcher to be between one and two percent of profit through the whole life cycle of creating an asset (RI.3.AP, 2024). In addition, the interviewed Material Passport-providers report how stakeholders in the AEC industry struggle with a lack of time to implement new technology: "Everyone is maxed out and working super hard. ... There's not enough time. There's too much work, so why would you do something extra if you don't have to?" (MP.1.PL, 2024). This overall competitiveness of the AEC sector is exacerbated by a general lack of efficiency as described by another researcher: "...in most projects, they are so inefficient you are running out of time to actually think of the next level of opportunities..." (RI.3.AP, 2024). This AEC-specific characteristic is both compounded by and part of the reason for the following technology adoption barrier: change resistance.

4.1.1.5 Change resistance (AEC-sector) – closed

The most significant AEC-barrier by quantity of mentioning surfaced throughout the semi-structured interviews was change resistance, counting almost half of all AEC-related codes. This rather broad barrier summarizes factors that prompt reluctance of construction professionals to be open to change, specifically the integration of a new software such as Material Passports or blockchain technology. They include a lack of financial incentives, a lack of vision, lack of time, technology resistance, and a general “fear of the new”.

All interviewees in one way or another describe financial incentives to be a major driver for change. However, if the application of a technology is considered to require significant effort with low economic return, it will face difficulties. Interestingly, a lack of financial incentives was not mentioned in connection to blockchain technology, but often when referring to Material Passport-barriers. In general, the circular transition is perceived to be a cost rather than provide reasonable financial benefits, and Material Passport-providers report to frequently encounter a sentiment the likes of “What’s in it for me?” (MP.1.MD, 2024).

This also feeds into the notion of a lack of vision, which is comprised of what the blockchain-researcher refers to as a lack of “entrepreneurial ambition” and a lack of ambition to innovate within the industry (RI.3.AP, 2024), and a lack of acknowledgement of i.e. asset owners for the benefit of novel digital technologies as reported by Material Passport-providers.

As a result of the unique market-competitiveness, AEC professionals also lack time, such as to change behaviours and habits amidst the pressures of daily routine. At the same time, a researcher also reports the notion of comfort with business as usual, saying “People don’t want to change because that means money and time and effort.” (RI.1.R, 2024).

Further, the participants in the study also refer to aspects of a phenomenon which could be described as technology resistance, including the resistance to embrace new technologies, despite theoretically being capable to learn and apply them (RI.1.R, 2024), as well as challenges related to age (MP.1.MD, 2024).

All these multi-faceted aspects cumulate in a general “fear of the new” among AEC professionals (MP.1.MD, 2024), ultimately limiting the wide-spread adoption of technology innovations like Material Passports and blockchain technology.

4.1.1.6 Lack of digitalization & technology literacy (AEC-sector) – closed

And lastly, a general lack of digitalization and technology literacy of AEC professionals was described by both industry practitioners and researchers, with one researcher expressing the lack of technology infrastructure to be a core challenge (RI.1.R, 2024). This seems to be a significant for the adoption of new technology as the very foundation for its implementation is limited.

However, the focus of the interviewees was mostly on the lack of technology literacy of professionals in the sector visible i.e. in human error in the application of existing technologies (RI.1.R, 2024). An example for this is the slow adoption of BIM. One practitioner reports “I know students from ETH, from ETH! They start working as an architect and don’t work with BIM!” (MP.1.MD, 2024). Another example that was mentioned is the difference in technology literacy in various national and economic contexts, such as the Netherlands versus Greece (RI.3.AP, 2024).

These aspects demonstrate the AEC sectors’ inadequate level of digitalization and its professionals’ poor technology literacy, which greatly hinders the adoption of new technologies such as Material Passports and blockchain technology, suggesting a need for educational and financial investment.

4.1.2 Material Passport-specific Barriers

The following section will present barriers specifically associated with the adoption of Material Passports according to quantity of mentioning, as they emerged from the data analysis: a lack of financial incentives, inadequate information provision, a lack of knowledge, technical practicalities, technology readiness, and regulatory frameworks. *Appendix E* summarizes these barriers, their

categorization in the PESTLE analysis framework, as well as provides detailed descriptions and corresponding evidence from the semi-structured interviews.

4.1.2.1 Lack of Financial Incentives (MPs) – closed

A lack of financial incentives emerged as a significantly often coded barrier to the adoption of Material Passports, mentioned 39 times across the interviews and including several factors, such as the profitability of not sharing information in the current economic landscape, the lack of foresight to capitalize on Material Passports other than through their marketing potential, and lastly high upfront costs.

There seems to be a consensus between the interviewed academics that Material Passports face the challenge that stakeholders tend to withhold data because they profit from not sharing it. One researcher mentions the reluctance of stakeholders such as manufacturers to publicly share material and component information (RI.1.R, 2024). This creates an asymmetry in information accessibility and essentially represents the phenomenon first described by Akerlof (1978), the “theory of lemons”, which discusses the power imbalance of a seller holding the information about a particular product, leaving the buyer vulnerable to adverse selection. In the case of Material Passports, market participants are concerned about losing competitive advantage while also profiting from the sale of access rights (RI.2.R, 2024). Assuming the interviewed Material Passport-providers belong to the beneficiaries of this dynamic, they did not mention this issue.

AEC professionals acknowledge that the current value of Material Passports is limited to the marketing value they offer, since they can be used for the application for sustainability certificates such as BREEAM and others (MP.1.PL, 2024). But the sector struggles to convey long term value of materials in financing schemes. This links to knowledge barriers, which will be described later. On a similar note, the second academic interviewed describes Material Passports as an enabler of network effects by defining a common language of how to describe and store data about existing assets (RI.2.R, 2024). This means the value of the system grows with its increasing adoption. Material Passports, for example, have the potential to enable residual material trade on a large scale. However, these benefits are difficult to convey at this early stage of technology dissemination.

Further, practitioners and scholars commonly mention high upfront costs as a barrier to Material Passport-adoption. It doesn’t surprise that the effort necessary for data collection, validation, and certification requires a significant investment. However, one Material Passport-provider adds the notion that high upfront costs need to be accepted by the market, which they were, if data transparency was either mandated or the industry would recognize the long term value of information provided by them, i.e. by unlocking the residual value of materials and components (MP.1.D, 2024). The lack of financial incentives leading to a reluctance to share data crucially decreases the benefits promised by Material Passports. This inadequate information provision will be further explored in the next section.

4.1.2.2 Inadequate Information Provision (MPs) – open

Naturally, a Material Passport is only as good as the information it holds. Therefore, inadequate information provision was another frequently mentioned barrier obstructing their widespread adoption. Reasons could include the availability and maturity of data provided, reluctance to share information, human error in data-input, as well as the impossibility to verify data.

Material Passport-providers discussed practicalities of the information provided. In the case of creating Material Passports for new buildings, it could be that 3D-, sometimes even BIM-models are provided. However, in most cases, information is scarce, as a Material Passport provider describes it: “I think the biggest challenge is that there is an overall lack of data available.” (MP.1.D, 2024). In that case, this provider uses a bottom-up approach to estimate the materials in a building called the Urban Mining Screener. It triangulates the year of construction, address, and typology (MP.1.PM, 2024). The completeness and accuracy of data is critical for the potential of Material Passports, but the provider also points out that 85% of information is better than none (MP.1.PM, 2024).

As mentioned previously, stakeholders currently profit from not sharing data as most poignantly summarized by one researcher: “So they ... basically don’t want anybody else to be able to make money from their IP.” (RI.1.R, 2024). Often, this protectionism of competitive advantage appears to be merely a feeling, illustrated by generally low levels of technology literacy in the construction sector. This issue, as well as a common lack of understanding of how to successfully use data, will be discussed more in later sections.

Closely linked to the fear of giving away intellectual property is the fear for data security. Although asset managers frequently recognize the value of making their portfolio data accessible, many believe that by turning over their data to a Material Passport-provider, they lose control over it (MP.1.MP, 2024).

A nearly inevitable issue with data collection is human error in data-input, frequently deemed the “garbage in – garbage out” principle (RI.1.R, 2024). Researchers discussed that not even the automation of data input using IoT devices or other digital technology can successfully mitigate this issue, adding: “It doesn't matter if you use a centralised system or a decentralised system. You always have that challenge.” (R.2.R, 2024).

Academics and practitioners unanimously discussed the difficulty of verifying data entries and effectively enforcing a single layer of truth (MP.1.PL, 2024). According to management of the interviewed Material Passport-provider, there is an active ecosystem of consultants such as KPMG and PwC who verify and certify data, although for large reimbursements (MP.1.D, 2024). Even if certifiers were public authorities, this raises questions about trust, mainly in the data provider or certifier (RI.1.R, 2024; RI.2.R, 2024). In addition, the legal expert emphasized the challenge of enforcing data accuracy for products entering the market from outside of the EU (LF.1.LA, 2024).

4.1.2.3 Lack of Knowledge (CE & MPs) – open

A lack of knowledge emerged as another adoption-barrier of Material Passports, although mentioned the least with a total of 15 codes across all interviews.

A lack of knowledge begins with the lack of awareness for the necessity of circular strategies in construction (RI.3.AP, 2024), as well as the necessity for accessible information to facilitate those. One Material Passport-provider i.e. is very clear about the fact that most homeowners simply don’t care about the data connected to their assets even though society is becoming more and more environmentally conscious and increasingly values sustainability measures (MP.1.D, 2024). With regard to the latter, Material Passports provide the basis for environmental reporting and regulation compliance (MP.1.D, 2024).

AEC professionals quite unanimously recognize a lack of acknowledgement in the sector for the potential that lies in the information provision by Material Passports, especially to find ways to innovate project financing. One practitioner explains the potential of residual value, suggesting that project financing could use residual value as equity at the end of the building's life if banks assessed the current calculated residual value, adjusted it based on their risk profiles, and then issued loans based on this adjusted value (MP.1.PL, 2024).

But not only banks are reluctant to see the potential within Material Passport-data. Another MP-professional also regrets that AEC-practitioners in general lack the creativity to capitalize on material and building information once it does become accessible (MP.1.MD, 2024).

The analysis of the knowledge barriers shows a lack of necessary awareness for circular practices within AEC, as well as of the inherent potential of Material Passports, which makes it difficult to effectively implement them into practice.

4.1.2.4 Technical Practicalities (MPs) – closed

Technical practicalities including questions about data storage and modelling, the complexity of data interoperability as well as establishing a link between the physical and digital asset came forward in the interviews a total of 25 times.

Data management, including storage and modelling as described in chapter 2 *Theoretical Background*, poses a challenge across industries, not only for Material Passports in the construction sector (RI.2.R, 2024). However, one researcher points out the particularly low levels of digitalization in the construction industry, which provide a bad foundation (RI.1.R, 2024). In addition, data storage systems and design options were not detailed, but the fear of data security and lack of trust in storage providers was resonated across all interviews (RI.3.AP, 2024). The long life cycle of buildings is crucial in this regard, because it results in the necessity to be able to store data for periods that might supersede the life of any stakeholder in the industry (RI.3.AP, 2024).

Further, practitioners and academics alike mention the complexity that lies within the interoperability of systems. Although not yet applicable, a Material Passport provider imagines this will be crucial in case a client was to transfer their data from one Material Passport platform to another (MP.1.PL, 2024). Likewise, issues of interoperability with other digital technologies such as IoT devices or BIM, not just with databases (MP.1.D, 2024), will surface as well (RI.1.R, 2024), in the case that data-entries and -management were automated to avoid human error in data-input.

Akin to B. Byers et al. (2022), the interviews raised the question of how to establish an unmistakable connection between the physical asset and its digital representation. A Material Passport-provider i.e. describes a possible circular ecosystem in construction, including secondary marketplaces, in which every building component was ideally tagged with a unique identifier (UID) to enable their unequivocal identification (MP.1.PL, 2024). However, this also exposes the significant challenges that lie in the practical implementation of that idea: "...who's going to pay to do that? Pay for the paper, pay for the system, pay for the labour to put ... the QR code ... on and then also educate all of the construction staff...?" (MP.1.PL, 2024).

These technological and logistical challenges emphasize the complexities of incorporating Material Passports into the construction sector, emphasizing the importance of solid digital solutions and data management systems.

4.1.2.5 Technology Readiness (MPs) – closed

Technology readiness, coded 20 times and implied by all participants to play a crucial part in the adoption of Material Passports, includes a lack of technology dissemination, a lack of viable use cases proving the use of the concept of Material Passports, and an overall lack of a systemic approach.

Lacking widespread dissemination, Material Passports are still described as a novel technology and circular business cases that could benefit from them or result from them, such as secondary marketplaces for salvaged materials, only exist in isolated cases (MP.1.PL, 2024; RI.2.R, 2024). Material Passports themselves, as discussed in chapter 2 *Theoretical Background*, lack a unifying scheme and standardization: "Everyone is kind of doing their own thing..." (MP.1.PM, 2024). This further supports the suggestion that they are still moving from an early adoption phase to a broader audience (Rogers, 2003).

This is emphasized by the fact that there is a lack of viable case studies that serve as proof of concept, unable to demonstrate Material Passports' value proposition on a grand scale. Instead, their current use case is limited to regulatory compliance and marketing, as described previously (MP.1.PL, 2024). The creation of use cases is therefore described by practitioners as pivotal to enabling industry-wide adoption, specifically in an industry that tends to be slow in the adoption of new technology: "They don't believe anything before they don't see it." (MP.1.MD, 2024). Therefore, another professional advocates for the integration of Material Passports in construction practice and their support at a systems level, including considerable investment, stakeholder engagement, user training, technical considerations such as interoperability, as well as regulatory frameworks (MP.1.PL, 2024).

These issues highlight the importance of a holistic approach to the implementation of Material Passports in AEC practice.

4.1.2.6 Regulatory Frameworks (MPs) – closed

The absence of regulatory frameworks emerged as the single most significant adoption barrier for Material Passports regarding their quantity of mentioning, mentioned 63 times. This barrier is complex and has to do with a lack of supporting legislation and industry standards (content & data-format), as well as determining what the costs for data collection and provision should be. There is also related legislation that impacts Material Passports' adoption and should therefore be treated as part of their regulatory framework.

As described in chapter 2 *Theoretical Background*, Material Passports are neither subject to any legislation nor industry standard. However, almost all interviewees share the consensus that their industry-wide implementation, needs the support of regulation on an EU level, for example by mandating material- and building-data transparency, thus passively incentivizing their adoption. The legal expert interviewed presents the Ecodesign for Sustainable Products Regulation (ESPR), which regulates Digital Product Passports (DPPs), as a possible foundation (LF.1.LA, 2024). Although opinions vary regarding the detail of legal arrangements, most of the interviewees agree: "...if you want to turn the EU into a circular economy, it can only be by force..." (LF.1.LA, 2024).

However, several practitioners also suggest regulation should take an active role, defining the content they are intended to detail, as well as their use case, scope, and data formats (MP.1.PM, 2024; MP.1.MD, 2024). On a more specific note, the legal expert suggested so-called European harmonised standards could deliver the foundation: "...they're very technical documents and a lot of times European acts, regulations or directives, they refer to these European harmonised standards, they kind of become like the law..." (LF.1.LA, 2024).

The same goes for Material Passport-standardization regarding data-formats: "...the big challenge is data. ... How do you guarantee that it's kind of the right format?" (RI.2.R, 2024). Again, the legal expert suggested European harmonised standards as a foundation. However, legislation will only demand that systems be interoperable, machine-readable, and easily accessible without prescribing the actual specifics (LF.1.LA, 2024).

Simultaneously, legislation should not neglect the cost for data collection and provision. As discussed previously, market parties need legislators to define the acceptable threshold of these upfront costs (MP.1.D, 2024). In case of European harmonized standards, regulatory bodies are actively disincentivizing Material Passport-adoption, as their access is currently kept behind a paywall (LF.1.LA, 2024).

And lastly, establishing a regulatory framework for Material Passports requires the integration of various digital markets legislation, such as applicable data protection law and the AI act (LF.1.LA, 2024). The lack of a legal framework creates substantial challenges to the implementation of Material Passports, emphasizing the necessity for EU-level legislative support. European harmonized standards might help standardize Material Passport content, data formats, and related costs.

4.1.3 Blockchain-specific Barriers

The following section will present barriers specifically associated with the adoption of blockchain technology. *Appendix E* summarizes the barriers, their categorization in the PESTLE analysis framework, as well as detailed descriptions and corresponding evidence from the semi-structured interviews.

The following paragraphs will describe the blockchain technology-specific adoption barriers that emerged from the data analysis according to quantity of mentioning: a lack of trust and general scepticism towards blockchain, a lack of knowledge, technical practicalities, technology readiness, regulatory frameworks, and the environmental impact of token mining. In the subsequent sections, a brief description is given for each barrier as it is described by practitioners.

4.1.3.1 Lack of Trust & General Scepticism (Blockchain) – closed

The most significant blockchain technology-adoption barrier regarding quantity of codes, was a lack of trust and general scepticism towards this novel technology. Mentioned in one third of all codes related to blockchain technology adoption barriers, a lack of trust and general scepticism towards blockchain technology was mainly linked to an overall bad reputation, the fear of misuse or abuse of sensitive data such as Personal Identifiable Information (PII) or Intellectual Property (IP), and the fear of job displacement due to its implementation.

Although unrelated to its use case in construction, blockchain technology is fighting a notoriously bad reputation as described by one researcher: "This is about drugs, guns, and illicit activities." (RI.3.AP, 2024). This was shared unanimously by all participants, either through the expression of that sentiment or by sharing the observation of it. For Material Passport-providers who want to establish a sustainable market share, this reputation is the most decisive factor for avoiding the technology. As an example, the Material Passport-provider interviewed throughout this research does implement single blockchain-inspired characteristics that are beneficial to their use case, such as awarding unique identifiers to Material Passports on their platform to time-stamp changes. But they refrain from marketing their solution as "blockchain-based" to not scare away potential clients: "Users ... don't even trust 100% what we provide them right now. And if you talk about blockchain, you lose the other half." (MP.1.MD, 2024).

The fear of abuse of Personal Identifiable Information (PII) and Intellectual Property (IP) is also closely related to the "outlaw status" of blockchain technology (MP.1.MD, 2024). The association of the term blockchain with cryptocurrencies, including news of Bitcoin exchanges being hacked and investors losing a lot of money, shape public perception and promote the idea that sensitive data could be stolen if systems were integrated with blockchain technology (RI.1.R, 2024).

Simultaneously, there is a part of the public that fears job displacement due to the implementation of blockchain technology. One researcher does in fact foresee some jobs becoming obsolete, however hand-in-hand with the rise of currently unimaginable jobs, as observed with the emergence of the internet (RI.1.R, 2024).

The widespread distrust of and prevalent scepticism towards blockchain technology in the AEC sector poses a significant challenge to its industry adoption. However, it is rooted in a lack of knowledge about it and its benefits and use cases, which will be discussed in the following section.

4.1.3.2 Lack of Knowledge (Blockchain) – closed

A lack of knowledge about blockchain is divided into a lack of understanding of the technology and its concepts and a lack of acknowledgement for its necessity for the integration with Material Passports, coded 16 times.

Both researchers and practitioners reported the observation of a lot of misconceptions surrounding blockchain technology in the market. They also reported their common denominator to be a general lack of understanding for the technology, resulting in aversion and rejection. As an example, a blockchain-researcher describes the misconception that people frequently confuse it as a data storage and data encryption tool (RI.3.AP, 2024). However, neither should the actual data sets be stored, nor the encryption be solved on the ledger. Blockchain technology is only designed to provide its fundamental properties, mainly immutability and non-repudiation, to transactional data, authenticating the data-recording instances and providing it with one single layer of truth. Storage should be solved using so-called decentralized data protocols or Web3-data storage systems (RI.2.R, 2024; RI.3.AP, 2024).

Although most of the participants had at least a basic understanding of the underlying concepts, functionality, and value proposition of blockchain technology, some also expressed scepticism towards the integration of Material Passports with blockchain technology, Material Passport-providers in particular. For example, a manager of the interviewed provider discussed the complexity and cost of technology implementation: "Why use blockchain for that? Why? That's way too complex. It's way too

expensive. Nobody understands it." (MP.1.D, 2024), showcasing a lack of acknowledgement for the necessity of Material Passport-blockchain integration.

4.1.3.3 *Technical Practicalities (Blockchain) – closed*

Another blockchain-adoption barrier that emerged from the interviews is that of various technical practicalities, including the complexity of interoperability in between systems and data protocols, the complexity of the so-called Oracle problem, the difficulty of designing participant roles and responsibilities within the blockchain network, and lastly the dilemma of the technical feasibility of prevailing issues without blockchain integration.

The discussion about how to set up a functional decentralized digital ecosystem and how to position blockchain technology and decentralized data protocols in relation to one another reveals various interfaces and the need for system-interoperability (RI.3.AP, 2024). And even if a blockchain network was designed to be internally coherent and perfectly interoperable, it cannot prevent faulty data-input from whomever or whatever it is interacting with. This is called the oracle problem. Instead, the researcher proposes to "...include the validator as one of the stakeholders that will need to maintain that data and they get reward for it...", to provide data authenticity (RI.3.AP, 2024).

Next, operability of a blockchain system is only given if a critical mass of participants is active in the network (RI.3.AP, 2024), and if their roles regarding read- and write-access rights, as well as the right to validate, are carefully designed (Ostrom principles): "So who is maintaining the system? Who is participating in the system? Who is using the resource but also needs to contribute back?" (RI.3.AP, 2024)

And lastly, the interviews resonated the prevailing question whether data storage, security, validation, and financial incentives couldn't also be solved with existing systems. Material Passport-providers are confident that traditional file systems are acceptable for data storage and security, that current certifiers or public authorities can address data validation, and that awarding unique identifiers (i.e. using GS1 methodology) is appropriate to provide data authenticity (MP.1.D, 2024). A blockchain-researcher, on the other hand, argues that blockchain technology must ultimately prove its technical superiority over traditional systems and that it comes down to what solution users place their trust in (RI.3.AP, 2024).

Interoperability, the oracle problem, Ostrom principles, as well as the assessment of blockchain's benefits over conventional systems provide the foundation for blockchain's technology readiness discussed in the following section.

4.1.3.4 *Technology Readiness (Blockchain) – closed*

First described in chapter 2 *Theoretical Background*, technology readiness was resonated in the interviews 16 times. Blockchain technology's dissemination in the AEC sector lacks use cases as proof of concept, as well as a lack of an overall systemic approach.

The study's participants blame the lack of a widespread adoption of blockchain technology in the AEC sector, specifically the lack of integration with Material Passports, on its relative novelty and the lack of viable use cases as proof of concept (MP.1.MD, 2024; RI.2.R, 2024). The interviewees expressed the need for the technology to develop further, with one researcher arguing that it must first explore extremes before finding a reliable and practical use case (RI.1.R, 2024). This researcher also emphasized the lack of a "killer app", a software application that so beneficial and successful that it validates the fundamental principles of blockchain technology for AEC and encourages the industry to adopt it systemically (RI.1.R, 2024). This illustrates the infancy of blockchain and Material Passport integration, explaining blockchains' need to demonstrate its benefits compared to existing systems (RI.3.AP, 2024).

This underscores the need of a systemic approach to the adoption of blockchain in AEC, including establishing the necessary infrastructure, creating incentive structures on an economic and regulatory level, as well as engaging stakeholders and fostering networks (RI.3.AP, 2024).

4.1.3.5 Regulatory Frameworks (Blockchain) – closed

Regulatory frameworks, mentioned nine times throughout interviews, can passively and actively disincentivize the adoption of blockchain technology by either the absence of supporting regulation or via legal concepts that inherently inhibit blockchain adoption.

There is no legislation actively incentivizing blockchain-adoption in AEC, constituting a passive barrier. However, participants also generally weren't in favour of it out of fear that even if it could drive development, it could be misdirected (RI.1.R, 2024), with one researcher and advocate for decentralized systems suggesting "As little as possible should be regulated." (RI.2.R, 2024). At the same time, participants describe how low levels of adoption also present legislators with the problem of not knowing what exactly to regulate (RI.1.R, 2024).

Regulations can also actively prevent the adoption of blockchain in AEC and the industry from exploring novel business models that emerge from its integration, such as building servitization models discussed in chapter 2 *Theoretical Background* (Azcarate-Aguerre et al., 2022). One Material Passport-practitioner shortly touched on the failure of the Products-as-a-Service (PaaS) due to the definition of ownership rights in current legal frameworks and mentioned the case of Mitsubishi Electric and their elevator servitization as a role model for PaaS-models as a circular strategy and legal precedent in the construction sector (MP.1.PL, 2024). Another problem raised by participants in the study was the danger of breaching privacy laws by sharing sensitive data of users (PII & IP) when integrating Material Passports and blockchain technology (RI.3.AP, 2024). The legal expert especially emphasized that the European Court of justice sees this as a significant problem due to its wide definition of Personal Identifiable Information (PII), saying "A unique identifier could already be a set of personal data." (LF.1.LA, 2024).

Therefore, regulatory frameworks not only provide barriers for Material Passport-adoption but also for the adoption of blockchain technology in AEC, particularly in its integration with Material Passports. Existing legal concepts were mentioned to be the main inhibitors to contribute to a slow dissemination of the technology in the AEC sector.

4.1.3.6 Environmental Impact (Blockchain) – closed

And lastly, the environmental impact of blockchain was brought up as a downside of the technology. One professional questioned the use of a technology as energy consuming as blockchain, if existing systems serve the same purpose with less impact (MP.1.D, 2024), referring to the high levels of energy consumed by the computing power necessary for token mining, particularly in proof-of-work consensus mechanisms as described by J. Li et al. (2019). Although only mentioned once throughout the interviews and innovations mitigating this issue, it was included in the barriers due to its adverse effect on blockchain technology reputation and the paradox of adopting it to enable the circular economy paradigm.

4.1.4 Summary Semi-structured Interviews

The previous sections presented important insights into the barriers preventing the AEC sector from adopting Material Passports and blockchain technology into industry practice by presenting the findings from method one, semi-structured interviews. These interviews were able to enhance the findings from desk research as can be seen in *Table 14*, revealing differences in focus between academic discourse and participants' experience and proving the value of including perspectives from researchers and practitioners alike. Making use of the PESTLE framework to methodically identify and structure adoption barriers related to the AEC industry in general, as well as those specific to Material Passports and blockchain technology, provides a clear exploration of the challenges encountered in putting these technologies into practice.

Table 14 juxtaposes these barriers. On first sight, there seems to be a large overlap in between literature and the interviews. However, although some barriers are mentioned in literature, they are not discussed in depth, including lack of digitalization (AEC-industry), lack of knowledge (blockchain),

lack of trust and general scepticism (blockchain), and environmental impact (blockchain). On the other hand, lack of financial incentives (blockchain) was not discussed in the interviews.

Table 14 Material Passport- and blockchain-adoption barriers; literature review vs. semi-structured interviews

PESTLE	Barrier	Literature review	Semi-structured interviews	Quantity of mentioning (interviews)
Political	Adverse economic-political context		✓	5
Economical	Chicken & egg problem		✓	5
	Industry fragmentation (AEC-industry)	✓	✓	2
	Lack of financial incentives (MPs)	✓	✓	39
	Lack of financial incentives (blockchain)	✓		0
	Market-competitiveness (AEC-industry)	✓	✓	9
Social	Lack of trust & general scepticism (blockchain)	✓	✓	24
	Change resistance (AEC-industry)	✓	✓	21
Technological	Inadequate information provision (MPs)		✓	35
	Lack of knowledge (CE & MPs)		✓	15
	Lack of knowledge (blockchain)	✓	✓	16
	Lack of digitalization & technology literacy	✓	✓	4
	Technical practicalities (MPs)	✓	✓	25
	Technical practicalities (blockchain)	✓	✓	9
	Technology readiness (MPs)	✓	✓	20
	Technology readiness (blockchain)	✓	✓	16
Legal	Regulatory frameworks (MPs)	✓	✓	63
	Regulatory frameworks (blockchain)	✓	✓	9
Environmental	Environmental impact (blockchain)	✓	✓	1

Chapter 2 *Theoretical background* did not feature a systematic literature review, making it difficult to provide insight into the quantitative weighting of these barriers in literature. Nevertheless, the exploration of literature reveals a strong focus of academia on solving technical aspects such as data storage and modelling of Material Passport solutions or the setup of the most efficient blockchain design option for a particular use case. On the other hand, *Table 14* showcases the quantity of mentioning of these barriers in the interviews, indicating a strong focus of participants on the relationship between financial incentives and regulatory frameworks to enable the adoption of Material Passports, as well as practical implications of inadequate information provision. Regarding blockchain technology-adoption barriers, interview participants prioritized the interrelation of knowledge barriers, lack of trust and general scepticism towards blockchain technology, and change resistance. Both literature and interviewees appear to value regulatory frameworks heavily.

4.1.4.1 Material Passport-adoption Barriers in AEC

The findings from method one of empirical research, semi-structured interviews, answer sub question one of this research.

SQ1: What are barriers to Material Passports?

Adoption barriers for Material Passports are made up of both AEC-general and Material Passport-specific barriers. First, the adoption barriers that hinder Material Passport-adoption in AEC, associated with technology adoption issues in AEC in general, are summarized in *Table 15*:

Table 15 AEC-general barriers for Material Passports adoption

PESTLE	Barrier	Subcategories
Political	Adverse economic-political context	Economy maturity
		National context - information accessibility
		National context – political system
Economical	Chicken & egg problem	Regulation or market incentives?
	Industry fragmentation	Numerous SMEs competing in a highly diversified market without dominant players
	Market-competitiveness	Slim margins
		Lack of time
Social	Change resistance	General inefficiency of industry
		Lack of financial incentives
		Lack of vision
		Lack of time
		Technology resistance
Technological	Lack of digitalization & technology literacy	Fear of the new
		Lack of technology infrastructure
		Lack of technology literacy & human error in application of technology
Legal	-	
Environmental	-	

Second, Material Passport-adoption barriers specific to Material Passports are summarized in *Table 16*:

Table 16 Material Passport-specific barriers for Material Passports adoption

PESTLE	Barrier	Subcategories
Political	-	
Economical	Lack of financial incentives	Not sharing data = profitable in current economic paradigm
		Current MP-inherent value limited to marketing value (certification etc.)
		High upfront costs (data collection, data validation, data certification)
Social	-	
Technological	Inadequate information provision	Lack of information availability & data maturity
		Reluctance to input data: fear of sharing trade secrets
		Human error in data-input
		Data-input verification (enforcement-barrier)
	Lack of knowledge	Lack of awareness for CE + need for information accessibility
		Lack of awareness for value of building and material data
	Technical practicalities	Digital storage & modelling issues
		Interoperability complexity) - in between systems/digital technology
		Interoperability (complexity) - physical-digital asset connectivity
	Technology readiness	Lack of technology dissemination
		Lack of cases as proof of concept, demonstrating viable use cases
		Lack of systemic approach
	Legal	Regulatory frameworks
Lack of MP-standardization (content)		
Lack of MP-standardization (data formats)		
Lack of MP-standardization (costs for data-provision/collection)		
Connected legislation		
Environmental	-	

4.1.4.2 Blockchain-adoption Barriers in AEC

The findings from method one of empirical research, semi-structured interviews, also answer sub question two of this research.

SQ2: *What are barriers to blockchain technology in AEC?*

The adoption barriers blockchain technology is facing in its adoption in the AEC sector are summarized in *Table 17*:

Table 17 Blockchain-specific adoption barriers in AEC

PESTLE	Barrier	Subcategories
Political	-	
Economical	-	
Social	Lack of trust & general scepticism	Bad reputation
		Fear of misuse/abuse of data (PII/IP)
		Fear of job displacement
		Technology resistance
Technological	Lack of knowledge	Don't understand it → aversion/scepticism
		Don't see necessity
	Technical practicalities	Interoperability (complexity) - in between systems/data protocols
		Interoperability (complexity) - blockchain-environment
		Ostrom principles
	Technology readiness	Technical feasibility without blockchain
		Lack of technology dissemination & viable use cases demonstrating proof of concept
		Lack of systemic approach
Legal	Regulatory frameworks	Lack of supporting regulation = passive barrier
		Legal concepts actively inhibiting blockchain adoption
Environmental	Environmental impact	Energy consumption of computing necessary for token mining

As detailed in chapter 3 *Methodology*, the findings from sub question one and two are synthesised to develop the coding schema for the analysis of method two: comparative case study analysis.

4.2 Findings from Comparative Case-study Analysis

The following chapter will present findings from method two, comparative case-study analysis, which aims at answering the sub questions three and four: “*What opportunities do BBMP-providers see in the adoption of their technology?*”, and “*What are challenges that current and early attempts at BBMPs face?*”.

Two examples from practice are explored and juxtaposed, in which organisations have integrated Material Passports solutions with blockchain technology in different ways. These case studies serve the purpose of identifying relevant opportunities of blockchain-based Material Passports (BBMPs) from the perspective of the examined case studies, as well as defining the challenges these BBMP-providers face in the adoption of their solution into AEC industry practice. The thorough analysis of these case studies presents a unique opportunity to gain insight from the early adoption of BBMPs to facilitate their further adoption.

4.2.1 Case Descriptions

The following section will introduce both case-studies, BlockMaterials and iov42, and describe their BBMP solution as well as DLT design option, before juxtaposing and comparing them accordingly. The presentation of findings from the two case studies, including opportunities in the form of relevant use cases and adoption barriers for each case, will follow thereafter.

Table 18 Case studies 1 & 2 fact sheet

	Case 1	Case 2
Name	BlockMaterials	iov42
Origin	Netherlands	England - UK
Core business	Research & applied research within CE in AEC	Software development, T&T
Employees	5-10	ca. 30
Passport solution	Blockchain-based Material Passport (BBMP), AEC only	Blockchain-based Digital Product Passport (BB-DPP), AEC-use cases
Scale	Building	Material/component
Operational scope	Netherlands	Global
BBMP target scope	Existing building stock (AEC)	New materials (AEC-use cases)
System design	Private permissioned	Private permissioned
DLT-design option	Public permissionless	Private permissioned
DLT-integration	Outsourced (ReCheck.io) - Ethereum	In-house development

4.2.1.1 Case 1 – BlockMaterials Case Description

BlockMaterials is a small research and development company based in the Netherlands with about five to ten employees. It functions as the backend provider for the integration of blockchain technology and Material Passports for their parent company Reusematerials (02_BM, 2024). Additionally, it provides Life Cycle Assessment (LCA) for building surveys issued by Reusematerials (BlockMaterials, n.d.).

As depicted in *Figure 12*, BlockMaterials is part of a larger ecosystem of organizations that aims to promote the circular economy in AEC, consisting of: Reusematerials conducting building survey and issuing Material Passports, Cirdax recording and storing Material Passports, BlockMaterials facilitating the blockchain-integration for Cirdax, Maeconomy certifying Material Passports industry-wide, Maaterialreserve as a secondary material marketplace, and Maaterials.com as a material ownership trading platform (03_BM, 2024). By setting up this elaborate network of organizations and stakeholders, all of which are essential for a circular economy in AEC, 03_BM (2024) describes that the founders of Reusematerials and BlockMaterials hope to unravel network effects to push the circular transition in the sector.

BlockMaterials operates with the financial backing of its parent company as well as on research grants, as reported by one member of its leadership, who points to several EU-funded research projects (01_BM, 2024). These include the recently completed Digital Deconstruction project (Interreg North-West Europe, 2019), which ended in the development of the Cirdax-blockchain interface, the very case studied in this research. Further, BlockMaterials is currently involved in the ongoing Demo-Blog project, which is focused on creating digital building logbooks to improve building data transparency in AEC (Horizon Europe, 2024).

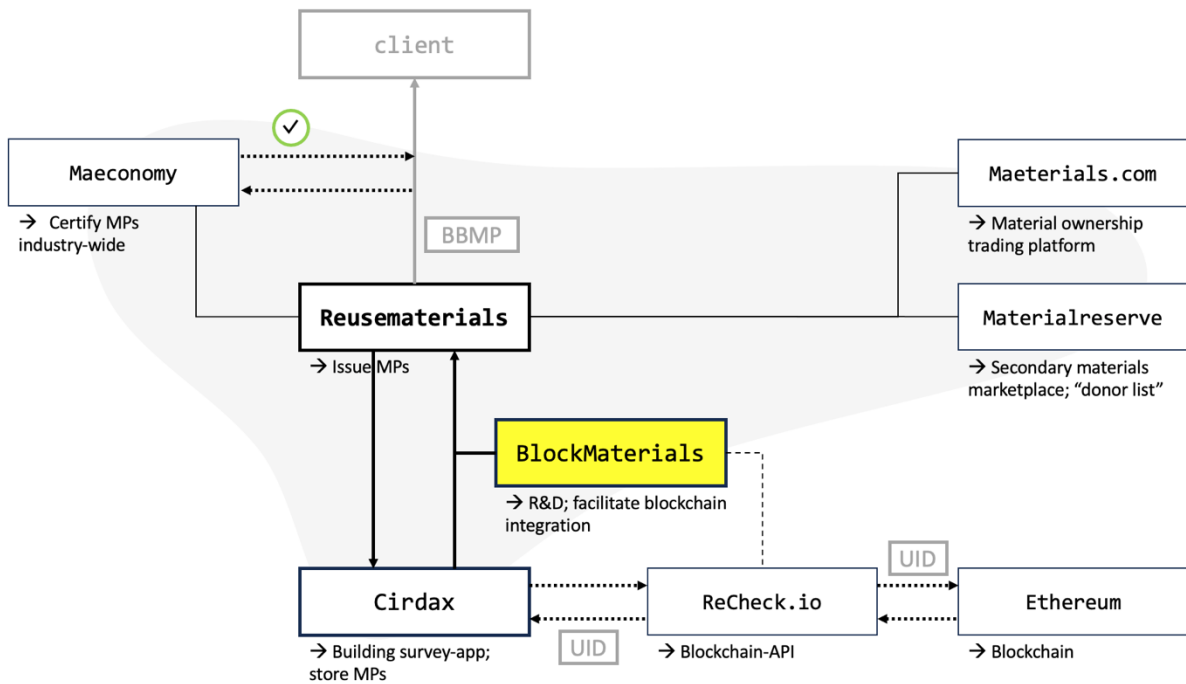


Figure 12 BlockMaterials' ecosystem for a circular economy in AEC

BlockMaterials' BBMP Solution

According to BlockMaterials-management, the company focuses on registering the existing building stock with their BBMP solution due to the potential impact of making material and building information of the largest fraction of the built environment accessible (01_BM, 2024). They refer to the fact that new construction only adds a few percent to the world's existing building stock per year – i.e. ca. 0,5% in Germany (European Commission, 2022a) – which in turn gives it great potential for scalability as a material bank for a circular economy in AEC (01_BM, 2024). Two employees claim BlockMaterials currently has about 200,000 sqm registered in Material Passports, convinced that they could register up to 100,000,000 sqm with subsidies worth 300,000,000€ (01_BM, 2024; 03_BM, 2024).

Applying the methodology of Cirdax, BlockMaterials primarily addresses the building scale, with the possibility of issuing a passport for a single component as well (02_BM, 2024). The process of creating a Material Passport with Cirdax involves tedious manual labour (02_BM, 2024), combining a top-down and bottom-up approach to information collection: step one includes desk research about the property, sighting drawings and cadastre information, researching the buildings material state, and reviewing the applicable building code. If available, Cirdax incorporates a 3D-model supplied by the client, otherwise commissions a point cloud-model (3D-scan on site), followed by a site visit to add any information about the building that isn't otherwise accessible. On site, materials are manually added to the Material Passport by taking pictures and adding dimensions. As part of the Material Passport issued by Reusematerials, Cirdax executes an LCA to visualize embodied carbon and other metrics. And lastly, the passport, in form of an infographic or an excel file detailing the material composition of the building (Appendix H), is delivered to the asset owner once it's finished (02_BM, 2024).

BlockMaterials' DLT Design Option

BlockMaterials assigns every passport a unique identifier (UID) that is hashed on the Ethereum blockchain (03_BM, 2024; ReCheck B.V., 2024), a decentralized blockchain network (ethereum.org, 2024a). This way, any change that is made to a Material Passport is automatically time stamped and a buildings life cycle history can be tracked seamlessly. BlockMaterials doesn't facilitate the blockchain-

integration themselves, instead they collaborate with the Dutch tech-start-up ReCheck.io, who are experienced in building interfaces (APIs) to existing blockchain solutions (01_BM, 2024).

Although Ethereum's zero-knowledge proof consensus mechanism can technically be classified as public permissionless (ethereum.org, 2024b), the system design BlockMaterials provide represents a 'private permissioned' setup. Zero-knowledge proofs are encrypted validation procedures that do not require the information that is validated to be shared during the validation (Goldwasser et al., 1989). BlockMaterials merely uses Ethereum to register changes to the unique identifier of the Material Passport, meaning datasets themselves are only accessible for read- and write-access to Cirdax and the client (asset owner) themselves, hence the classification 'private permissioned'. Data is safely stored in IPFS, a file sharing peer-to-peer network for decentralized data storage that requires access rights (03_BM, 2024).

4.2.1.2 Case 2 – iov42 Case Description

iov42 is a British technology start-up company of around 30 people that was originally established in 2016 as a blockchain technology provider, having designed a novel consensus mechanism called Distributed Random Master Election (DRME) as response to early blockchain applications that were energy consuming and required users to openly share data (01_iov42, 2024; 02_iov42, 2024; iov42, 2024). By developing individual use cases for industry partners based on their blockchain-inspired infrastructure, iov42 evolved and now operates a material traceability platform for various industries called Interu (02_iov42, 2024). The company aims to promote information integrity, accountability, and authenticity throughout material supply chains by embedding trust in the transactions of commodities (02_iov42, 2024; Interu by iov42, 2024).

iov42 BBMP Solution

The two use cases prominently marketed by iov42 as well as referred to in this case are the "Timber Chain" and "Steel Chain", designed to provide blockchain-based Digital Product Passports for the respective supply chains of large timber and steel manufacturers to trace material provenance data and improve certification processes for regulatory compliance (iov42, 2024c; iov42, 2024a). These two use cases are applied in the AEC industry in a wider sense, as iov42's solution provides the potential to track and trace these materials throughout their whole life cycle, including their service life in the built environment. Accordingly, their BBMP-solution adopts a material scope.

iov42's track-and-trace platform Interu allows companies to register materials at their source, issue Digital Product Passports (DPPs) for them, and track them along their complete supply chain by representing their quantities as transactions on the ledger of iov42's own blockchain (Bridgland, 2024; Interu by iov42, 2024). Data entry in the beginning of the supply chain involves manual entry, such as time and date of production, the quantity of products in a batch, their dimensions and material properties, as well as uploading relevant documentation such as material testing reports (iov42, 2022). From then on, this information can be continuously updated as the materials move through the supply chain.

iov42 BBMP DLT Design Option

The blockchain integration developed by iov42 features a 'private permissioned' DLT-design. First, iov42's solution is inherently 'private' because different platforms are set up for different industries ('Timber Chain' & 'Steel Chain'), meaning only industry participants who interact with the specific materials throughout their life cycle can join the network and have read-access. Additionally, a member of iov42-management explained the steel passport in *Appendix I* by pointing to the ability of a manufacturer to customize read-access within the same passport document: "Manufacturing date, where the pipe was made, what the dimensions are, CO2... that is something that in this case the producer ... is comfortable sharing publicly, but there's other information that they... monetize and they sell to the customers downstream." (01_iov42).

What is unique to the approach of iov42 is, that not only does it make all identities within the network transparent, but also include trusted third parties (TTPs) as nodes in the network (01_BM, 2024; Bridgland, 2024). This is intended to enable trust of users in the network itself as well as in the data other participants record. These TTPs, i.e. conventional validators or certifiers who industry professionals already place their trust in, endorse claims (01_iov42, 2024). This can be done in two ways: either a certifier physically inspects the product and compares it to its Digital Product Passport, accessed through the Interu platform, or another participant down the line in the supply chain endorses the claim in the passport document (01_iov, 2024). This also illustrates the ‘permitted’ characteristic of iov42’s blockchain design, as various nodes have differently distributed write-access. Roberts (2023) emphasizes this core promise of iov42 to safeguard sensitive information and allow only authorized parties to have access essentially promotes trust in the sharing of important circular economy-relevant information.

In contrast to the original blockchain consensus mechanism as described by Nakamoto (2008), the Distributed Random Master Election (DRME) mechanism doesn’t distribute the transactions that need to be validated to the whole network of nodes but instead to selected trusted nodes. It selects a participant at random to lead the consensus coordination for each transaction, which lowers the energy consumption necessary for computing as well as improves its overall performance (iov42, 2024b).

4.2.2 Case-study Comparison

As can be seen in *Table 18*, BlockMaterials and iov42 fundamentally differ. They not only have a different national origin, but also industry background: BlockMaterials has its origin in the AEC industry, iov42 in the software development or blockchain domain. BlockMaterials is a research entity of a larger ecosystem of companies trying to create and showcase circular economy network effects in AEC, while iov42 is a self-profitable start-up company that develops software solutions for various industries that so happen to also be applicable to the AEC industry. BlockMaterials facilitated the creation of an API for the connection of an existing Material Passport solution and an existing blockchain technology, whereas iov42, as software developer, built its own blockchain technology and set up its own Digital Product Passport solution on top of that. Additionally, BlockMaterials’ BBMP use case is specifically targeting AEC and the service life of buildings and their materials as well as at their reuse at their end-of-life, whereas iov42 primarily applies their technology to other sectors, covering supply chains from material origin to material delivery (i.e. on site).

As described in chapter 3 *Methodology*, both cases are an organization which provides an AEC industry-applied product passport that is integrated with a blockchain technology. Albeit being the most important overlap, the BBMPs of both companies also reveal significant differences, such as a different target scope (building level vs. material level) and a different level of maturity of both the organization and their respective BBMP-solution. The latter can be observed i.e. in the format and presentation of the BBMP-product (*Appendix H & I*). BlockMaterials issues a pdf-infographic using the Cirdax app to detail the material composition of an existing building (*Appendix H*). On the other hand, iov42 provides their users with access to a sophisticated online platform for the ‘Timber Chain’ (Interu by iov42, 2024) and a detailed online passport enriched with relevant product sheets, testing documentation, and certification for the ‘Steel Chain’ (*Appendix I*).

As depicted in *Table 18*, case one and two feature the same system design, classified as ‘private permitted’, although executed in slightly different ways: BlockMaterials outsources the integration of their Material Passport with the Ethereum blockchain, whereas iov42 is solving blockchain infrastructure in-house.

Although the obvious differences of both cases complicate their comparability, their common denominator being a product passport tool with an application in the AEC sector is reasonable enough

to qualify them for this research. If anything, they illustrate the variety of necessary tools, targeted lifecycle stages and scope, as well as their potential interoperability for a successful circular economy implementation.

4.2.3 BBMP Opportunities

The following section will outline the most relevant opportunities as described by BlockMaterials' and iov42 leadership and employees in form of use cases. *Appendix F* outlines the mentioned opportunities with quotes from the interviews conducted for this case study. These findings answer sub question three of this research.

SQ3: What opportunities do BBMP-providers see in the application of their technology?

4.2.3.1 Facilitating Future Contracts for Material Reuse

BlockMaterials proposes that the circular economy is all about whether one can make a future contract and facilitate the transfer of ownership before delivering the actual physical asset (01_BM, 2024). Or the other way around: making future contracts is about the question whether the transfer of the physical material, for which the ownership has been transferred years ahead, can be guaranteed at the end of that materials service life. BlockMaterials is adamant that the integration of blockchain technology and Material Passports can facilitate this, because as an integrated solution they award "property rights", meaning unique identities, to the materials and components (01_BM, 2024; 03_BM, 2024). This enables two marketplaces: "You have ... the moment it [the material] actually physically becomes available, and you have the rights to that moment." (03_BM, 2024).

4.2.3.2 Secondary Material Marketplace

Closely connected to "future contracts" is the potential to establish secondary material marketplaces. If materials in buildings were registered, their digital representations in form of Material Passports could be uploaded to a dynamic online material marketplace where these secondary materials could be traded (01_BM, 2024; 03_BM, 2024), similar to eBay for example. One BlockMaterials leader calls this a "donor list" (03_BM, 2024).

4.2.3.3 Active Material Stock Trade ("Fluid Asset" Trading)

BlockMaterials also describes the active trade of the ownership rights of materials that are bound to an asset (03_BM, 2024). Given the precondition that all materials in a building were registered and represented by a BBMP as a legal document, their ownership as sort of a share in a physical asset could be traded like common stocks are traded at the stock exchange. This could unlock the financial potential currently locked-in in the built environment in form of (residual) material value (03_BM, 2024). BlockMaterials' leadership proposes that the Dutch real estate market is approximately worth €2,8 trillion, roughly 10-30% of which is in the value of materials, all of which represent potentially tradeable assets. They propose the benefits of this would be twofold: for one, it would make real estate investments more accessible, enabling more people to build equity. On the other hand, cash flow could be additionally generated by platforms that facilitate the trade and collect trading fees (03_BM, 2024).

4.2.3.4 PaaS (Products-as-a-Service)

All BlockMaterials representatives also point to material servitization, the circular economy business model (CEBM) called "Products-as-a-Service" (Paas) (01_BM, 2024; 02_BM, 2024; 03_BM, 2024). This novel business model describes developers or contractors that, instead of buying and owning, lease the materials for their building. This way, the manufacturer of the materials and components retains ownership, as well as the responsibility for the material, i.e. regarding maintenance, take-back and reuse (Azcarate-Aguerre et al., 2022). Naturally, BBMPs lend themselves as a facilitator for this CEBM because they provide the record of ownership as well as the potential for component track and trace (T&T). The benefit of that is not only the facilitation of circular practices in the construction sector, but

also lower construction costs, which in turn could drive housing development and reduce the costs for living (03_BM, 2024).

4.2.3.5 Residual Material Value Transparency

BlockMaterials further explains how the registration of materials in buildings makes their residual value transparent (03_BM, 2024). In De Simplist (2022), the BlockMaterials representative discusses how making residual value transparent can lead to lowering financing costs, estimated by one BlockMaterials participant in case study one to amount ca. 10-30% of the total building costs (03_BM, 2024).

4.2.3.6 Life Cycle Assessment (LCA)

Lastly, a BlockMaterials employee outlined the current main use case for BlockMaterials BBMP-solution, which is the Life Cycle Assessment (LCA) for regulatory compliance (02_BM, 2024), also reflected in (De Simplist, 2022). Evidently, based on the proof of a carbon footprint and the promise to reuse a certain number of materials, a lot of clients use LCAs to persuade authorities to approve demolition or other building activity such as retrofitting (02_BM, 2024). Further, the BBMP is used as a visualization and certification tool of building material composition, which helps convince clients or authorities of a compelling business case that aims at material reuse (02_BM, 2024).

4.2.3.7 Full Asset Tracking throughout Material Life Cycle

iov42's main use case as discussed by interviewees from case-study 2 is the track and trace (T&T) of materials along their supply chain (02_iov42, 2024). One iov42-participant suggests that materials could also be traced further than the "final destination", meaning throughout the whole life cycle of a material (02_iov42, 2024). However, iov42 has not yet had that case due to the long lifecycles of timber and steel. Basis for the full asset tracking throughout a materials lifecycle include the fundamental properties of blockchain technology, as well as the specific design of iov42's BBMP solution: immutability, timestamping and notarization of transactions, providing a full historic record of material data, transparency of nodes, establishing trust in the notarization of transactions, as well as decentralization of transaction validation, which ensures scalability and trust in the network (01_iov42, 2024). And it is the scale of data and the need for traceability over big periods of time that, according to iov42 management, make the integration of blockchain technology exceptionally useful for Material Passports (01_iov42, 2024).

4.2.3.8 Regulatory Compliance

Traceability and data authenticity lead to the use case of regulatory compliance. This additional layer that BBMPs add on top of the ownership of products makes the digital records of physical assets and the claims about them auditable because the blockchain-integration provides one "single layer of truth" for these claims reported on Material Passports (02_iov42, 2024). This is important for compliance with i.e. environmental reporting regulations, certification of materials for a specific use, or insurance cases (01_iov42, 2024; Bridgland, 2024), especially if materials enter different markets and regulatory systems throughout their lifecycle (02_iov42, 2024). As mentioned previously, BlockMaterials shares this use case (02_BM, 2024).

4.2.3.9 Premiums for Product Transparency

According to iov42, companies including asset owners, will be able to charge market premiums on products that provide added transparency about the provenance and history of a material or component (01_iov42, 2024). This is because actors along the supply chain invest resources to collect information and supply chain transparency, but also because end users will be willing to pay for the access to this information. The second iov42-participant adds that providing this material transparency will give companies competitive advantage in future (02_iov42, 2024).

The following *Table 19* presents the final list of compiled BBMP-opportunities as identified in the comparative case-study analysis, including a short description. BlockMaterials discusses a lot of potential future use cases that include, at times, visionary ideas about future dynamics and paradigm shifts, while iov42 focusses on the description of use cases that are tangible and related to the current implementation and associated benefits of their technology. This underscores the observation about the level of maturity visible in the presentation of the respective BBMP-solutions (*Appendix H & I*).

Table 19 Compiled list of BBMP-opportunities

BBMP-opportunities	Description	Case
Facilitating future contracts for material reuse	Awarding unique identities to materials through the adoption of BBMPs enables the transfer of ownership of a material before delivering the physical asset.	1
Material marketplaces	Online platforms facilitating the trade of registered secondary materials, similar to eBay.	1
Active material stock trade	Active trading of ownership rights to materials bound in buildings, making real estate investment accessible and generating additional cash flow through trading fees.	1
PaaS (Products-as-a-Service)	Facilitated through track-and-trace (T&T) based on BBMPs, manufacturers retain ownership of materials in buildings and lease them to the developer.	1
Full asset tracking throughout material life cycle	Track-and-trace (T&T) of assets along their supply chain with potential for full lifecycle tracking facilitated by fundamental properties of blockchain technology and Material Passport-integration.	2
Residual material value transparency	Registering building materials makes residual value transparent, lowering project financing costs for asset owners.	1
Premiums for product transparency	Manufacturers will charge market premiums for transparent material provenance data, compensating investments for data collection.	2
Life cycle assessment (LCA)	LCAs based on building inventory for regulatory compliance.	1
Regulatory compliance	Blockchain provides “single layer of truth” for reporting, making Material Passports auditable and facilitating regularoty compliance.	1, 2

4.2.4 BBMP Adoption Barriers

The following section will outline the most relevant BBMP-barriers as described by BlockMaterials’ and iov42 leadership and employees for the adoption of their solution. *Appendix G* summarizes these barriers, their categorization in the PESTLE analysis framework, as well as detailed descriptions and corresponding evidence from the case-study interviews. These findings answer sub question four of this research.

SQ4: What are challenges that current and early attempts at BBMPs face?

For reasons of avoiding repetition, barriers will not be explained individually as they are compiled from method one, semi-structured interviews – a detailed description can be found in section 4.1 *Findings from Semi-structured Interviews*. Instead, this section will focus on the emphasis of cases one and two as they emerged from method two, comparative case-study analysis.

Participants in case-study one mainly focus on economic barriers and disincentivizing dynamics as the main barriers for BBMPs in AEC. BlockMaterials frequently mentions a lack of financial incentives, both for the adoption of Material Passports and blockchain technology in AEC due to both technologies fundamentally challenging the existing economic and regulatory paradigm. Noteworthy aspects of a

lack of financial incentives for Material Passports include the lack of incentives for market parties to share information, anxious of losing a competitive advantage if they do, which participants link to a lack of investments in the technologies that can facilitate that information sharing (BBMPs). Participants also describe barriers with a lack of financial incentives for blockchain technology's integration with Material Passports. Market parties are not yet able to capitalize on potential network effects that BlockMaterials suggests will emerge from the adoption of BBMPs.

This leads to the so-called chicken & egg problem: providers have to invest in a technology to get it into the market, without a supporting regulatory system or economic environment that welcomes its adoption, such as existing users and infrastructure. Participants in case-study 1 link this barrier to technology readiness, which was also discussed frequently. There needs to be proven market demand and tangible evidence of the technologies' potential. Essentially that's what the participants are describing: a lack of technology dissemination and viable use cases that demonstrate the proof of concept.

Further, market demands are reported to be significantly restrained by the existing regulatory context with a lack of supporting regulation, lack of standardization in terms of content and data formats, as well as legal concepts actively prohibiting blockchain adoption for novel business models. These barriers are mentioned second most frequently.

Case study one-participants also describe compounding effects of barriers. For example: because there is a lack of incentives to share information, there is quite simply also a lack of it. This is also due to the industry's poor overall digitalization, which in turn is closely connected to technology literacy in the industry and a lack of knowledge about the underlying concepts and technologies of BBMPs.

Interestingly, technical practicalities aren't reported to be the most impactful challenges by BlockMaterials-representatives, although interoperability challenges are acknowledged. The question of how to register the whole existing building stock i.e. is discussed on a technical level, but eventually participants don't fundamentally question the technical feasibility, rather keep emphasizing a lack of "scale and scope" and an overall lack of investments into the wide-scale adoption of BBMPs (O1_BM, 2024).

As participants from case-study two are familiar with the supply chain before the materials arrive on the construction site, they also report barriers that manufacturers have, rather than that of developers, asset owners, contractors, or designers.

Economic barriers are mentioned by iov42, but only regarding the lack of incentive for manufacturers to collect and share data. Participants describe how difficult it is for parties at the end of the supply chain to compile all the information that they are obliged to report (carbon footprint, material provenance etc.), because actors at the origin of the materials don't have the necessary infrastructure, financial incentive, legal obligation, or technology literacy to collect and share the necessary data in the first place.

This is frequently described by participants of case-study 2 to feed into an overall lack of information availability. Compounded by a reluctance to input data, interviewees emphasize problems with human error in data entries and issues with the verification of that data, closely related to a lack of digitalization and technology literacy.

However, the most reported barrier by iov42-representatives was "technical practicalities". They focus on how data is entered, but also data quality and maturity. Further, the interoperability of systems is highlighted, meaning the need for a seamless integration of technologies and existing data management systems to avoid frustration which may end in the abandonment of technology implementation. Especially data quality is emphasized as a practical barrier of the adoption of iov42's BBMP-solution. As an example, an employee reports how a handler down the line of the supply chain might have a differently calibrated measurement tool and tries to enter data to the Passport that

slightly differs from its original data entry, which the blockchain algorithm prohibits (02_iov42, 2024). To mitigate this practical challenge, iov42 had to find a way to allow certain thresholds of deviance in data entries for the same material.

Compounding the challenges with technical practicalities, interviewees of case-study 2 also frequently report a lack of digitalization and technology literacy for the adoption of their BBMP-solution, which they link to knowledge-barriers surrounding mainly misconceptions about blockchain technology and its use cases.

And lastly, the reported barriers related to legal frameworks focus on standardization issues – not only the content of BBMPs and data formats for interoperability reasons, also how the costs for data collection should be distributed.

Table 20 shows the overlap of mentioned BBMP-adoption barriers in between method one and two, semi-structured interviews and comparative case-study analysis.

Table 20 Comparison of case studies 1 & 2 - BBMP-adoption barriers

PESTLE	Barrier	Case 1 – Block-Materials	Case 2 – iov42
Political	Adverse economic-political context	✓	✓
Economical	Chicken & egg problem	✓	
	Industry fragmentation (AEC-industry)		
	Lack of financial incentives (BBMPs)	✓	✓
	Market-competitiveness (AEC-industry)		
Social	Lack of trust & general scepticism (blockchain)	✓	✓
	Change resistance (AEC-industry)	✓	✓
Technological	Inadequate information provision (BBMPs)	✓	✓
	Lack of knowledge (CE & MPs/ blockchain)	✓	✓
	Lack of digitalization & technology literacy	✓	✓
	Technical practicalities (BBMPs)	✓	✓
	Technology readiness (BBMPs)	✓	✓
Legal	Regulatory frameworks (BBMPs)	✓	✓
Environmental	Environmental impact (blockchain)		✓

Most barriers are mentioned in both data collection methods, with case-study 1 revealing the greatest deviation of a total of four barriers out of 14 BBMP-adoption barriers not mentioned.

Although both case studies almost entirely align in all BBMP-barriers, their emphasis on subcategories differs. Nevertheless, significant economic barriers to the adoption of BBMPs are highlighted in both case studies, including a lack of financial incentives resulting in the reluctance of market participants to provide data. Further, as part of the technological barriers, both studies highlight the industry's general lack of digitalization and technology literacy responsible for poor data quality and maturity. The participants in both situations also emphasize the impact of legal challenges, describing the necessity of standardization to promote interoperability and enable wider adoption, particularly regarding data formats and content.

The differences both case studies reveal in the barriers that they encounter include economic and legal issues, technical practicalities, and the reasons for inadequate information provision. Participants in case-study 1 primarily focus on the larger regulatory and economic landscape, frequently highlighting the chicken & egg problem, as well as the requirement for BBMPs to demonstrate their potential in viable use cases and thus established market demand. On the other hand, participants in case-study 2 focus more on the technical aspects of the supply chain, such as practical problems with data input and the requirement for seamless technology integration. Additionally, case-study 2 emphasizes specific problems that manufacturers encounter in the application of their technology including how to cope with the loss of access keys – practicalities that case-study 1 did not reveal, again suggesting a difference in technology maturity of their BBMP-solution.

Table 21 presents the final list of BBMP-adoption barriers, structured according to the PESTLE framework of analysis.

Table 21 Compiled BBMP-adoption barriers

PESTLE	BBMP-adoption barrier
Political	Adverse economic-political context
Economical	Chicken & egg problem
	Industry fragmentation (AEC-industry)
	Lack of financial incentives (BBMPs)
	Market-competitiveness (AEC-industry)
Social	Lack of trust & general scepticism (blockchain)
	Change resistance (AEC-industry)
Technological	Inadequate information provision (BBMPs)
	Lack of knowledge (CE & MPs/ blockchain)
	Lack of digitalization & technology literacy
	Technical practicalities (BBMPs)
	Technology readiness (BBMPs)
Legal	Regulatory frameworks (BBMPs)
Environmental	Environmental impact (blockchain)

4.2.5 Summary Comparative Case-study Analysis

This chapter presented method two of empirical research, comparative case-study analysis, which aimed at answering the following two sub questions: *What opportunities do BBMP-providers see in the application of their technology?* and *What are challenges that current and early attempts at BBMPs face?* Two examples from practice were compared, in which organisations integrated Material Passport solutions with blockchain technology in different ways, identifying relevant BBMP-opportunities in form of current and future use cases, as well as the respective barriers they face in their adoption into AEC practice.

5 Discussion

This chapter will discuss the research design and findings, as well as outline limitations and recommendations.

It was imperative that, as a contemporary phenomenon, the potential of BBMPs was studied in its real-life context. Especially given the nascence of the technology and phenomenon, an exploratory, multi-method research approach featuring semi-structured interviews followed by a comparative case-study analysis was appropriate.

The described methods were able answer the research questions. Nevertheless, several observations remain open to discussion.

Compared to literature, a lack of financial incentives for blockchain wasn't mentioned in interviews or case studies as a BBMP-adoption barrier. Although discussed with participants that blockchain will not be used for data storage, because that would be impractical and too expensive, the barrier was not brought up in relation to how blockchain technology is intended to be integrated with Material Passports. It can only be assumed that this is because the interviewees were themselves providers of the technology and thus inclined to believe that there is a market for their solution, and sell the associated benefits as opposed to doubting the economic return.

Also, it should be questioned if network effects, as described by BlockMaterials, are possible if most of the representatives in the whole network of companies overlaps. Especially the impartiality of a Material Passport certifier should be treated with caution if the sister company issues the BBMPs themselves.

5.1 Stalemate Situation

It appears the proposition of integrating Material Passports with blockchain technology has the potential to put the adoption of Material Passports into a stalemate situation. Industry professionals generally react with caution, to say the least. This is surprising given the promises expressed by practice in the potential use cases described in section 4.2.3 *BBMP Opportunities*, as well as the opportunities described in literature, including improving the technical performance of Material Passports. As proposed by Q. Li & Wang (2021) and Hunhevicz et al. (2023), the integration of blockchain technology and Material Passports can provide considerable efficiency gains in data management and validation, deliver longevity to the storage of material-, component-, and building-data, improve stakeholder collaboration along the value chain of materials throughout their lifecycle, and incentivize sustainability practices due to the auditability of information when integrated with blockchain. However, it is also blockchain technology that adds another level of complexity to Material Passports, a concept that is already difficult to comprehend for large parts of the sector. Participants of the expert interviews as well as the case-studies describe change resistance as an important barrier to the adoption of BBMPs, grounded in a general lack of understanding for the technologies, but compounded by a lack of trust and severe scepticism towards blockchain technology.

It should be precisely the barriers Material Passports face, especially a lack of financial incentives, that should incentivize the integration with blockchain technology. However, as there is no proof yet that the network effects can unfold as described by BlockMaterials, the industry remains in a state of inertia. To advance innovation and move on from this state, a series of significant challenges including challenging existing legal concepts, such as the definition of property rights in private law, would need to be overcome.

5.2 Secondary Material Marketplaces

As described by participants in the interviews, the low-tech variant of an active secondary material trade would be a demolition company that sells salvaged materials they harvested from decommissioned buildings and contractors that buy certain batches of components that can be used for non-structural purposes. Several cases of these exist including the German [restado.de](#) (2024) or the Dutch [materialenmarktplaats.nl](#) (2024), however they are very small scale, still represent a niche service, and don't have any Material Passport integration.

The future of secondary material marketplaces for the architectural practice, however, could be more sophisticated, empowered by BBMPs: integrated with blockchain-based Material Passports, they trade a wide range of materials and components either still bound in a building, soon to be available, or already disassembled and ready to use. These material marketplace platforms could then be integrated with BIM as an API or software extension, so that a designer could scout materials in the region of their project site and integrate the available resources directly into the BIM-model. Ideally, Material Passports would then have IFC files for the direct integration, including the historic information regarding material provenance, maintenance activities, certification documentation and other necessary data for re-certification and reuse.

5.3 Active Material Stock Trade (“Fluid Asset” Trading)

Apart from secondary material marketplaces, one of the opportunities BBMP-adoption presents was the idea of active material stock trade or “fluid asset” trading. This describes the concept of trading the ownership rights to materials bound in buildings with the idea of making real estate investment accessible and generating additional cash flow by charging trading fees.

BlockMaterials calls the ownership rights connected to a physical material “liquid asset”, made accessible by registering the material and hashing the digital record on the blockchain-ledger (03_BM, 2024). This way, the rightful ownership of a material in a building can be identified, authenticated, and subsequently traded, analogue to common stock at the stock exchange. Another participant of the semi-structured interviews compared this to a “long position” in finance due to the dynamics of the material price and the unknowns connected to the future lifecycle of materials until recovery. This comparison seems appropriate considering the long holding time and dynamic value as described by Simon Duindam (2022).

Accordingly, BlockMaterials describes not only the complete separation of the ownership of the house and the people that live in it (like in conventional lease contracts), but also the separation of ownership of the house and the organization that operates it. Essentially, a housing corporation would instead of going public with company shares, offer the materials in its properties to the market for asset trading. This might hold considerable value; however, questions remain. For example, considering the moment of deconstruction, “investors” or “asset owners” of single materials in a building would likely retain their ownership of the material in case it was recovered and then reused in another project. In that case, nothing would change for the “asset owner”, the material would simply change location. However, what if the material had reached its end-of-life and was up- or downcycled? Would the “asset owner” be forced to sell their ownership to the handler of the physical asset or just lose their investment?

And further, what would the owner-user relationship look like? A BlockMaterials-representative describes there would be a normal housing association acting as the landlord towards the tenants, who wouldn't even notice a difference (03_BM, 2024). But it is the reliabilities in between the housing association and the rightful owner of a material, which remain unclear. Assuming legal barriers as described in Azcarate-Aguerre et al. (2022) weren't a problem, the materials-trading platform facilitating the ownership rights trade could issue PaaS contracts with every sale of an asset in between the housing association handling the building and the new “asset owner”.

5.4 Platform-lock in

Material Passports are objectively a great thing to have because they can make the vast number of resources stored in our built environment accessible by registering the corresponding material data. Ideally, this building information should be treated as a common pool resource and made transparent as an open source good to enable circular practices in AEC. However, market dynamics prohibit this transparency and Material Passports are in fact only accessible to the owners of the corresponding physical assets. This is because the large upfront investments for data aggregation and hosting disincentivize asset owners and Material Passport providers to share this information publicly, resulting in a so-called “platform-lock in” of circular economy-relevant information.

Without this building information transparency, previously discussed BBMP-use cases such as “Secondary Material Marketplace” and “Active Material Stock Trade (“Fluid Asset” Trading)” wouldn’t exist. Governments could either mandate Material Passport providers to share datasets and passport documents in a public data base. More likely, however, secondary material marketplaces or material stock trading platforms will purchase this information via licensing formats and offer it to their users in form of subscriptions or memberships. In this case, blockchain integration is necessary to facilitate transparency while safeguarding information authenticity and managing read- and write-access rights, particularly regarding the protection of sensitive information (PII & IP).

Therefore, avoiding platform-lock in through blockchain integration is closely linked to the opportunities for novel business models that this integration provides.

5.5 How accurate does data need to be?

Information maturity on Material Passports is highly dependent on the data sources and differs significantly in between the BBMPs of the examined cases in section 4.2 *Findings from Comparative Case-study Analysis*. This raises the question of how accurate data needs to be for a true circular built environment.

The unmistakable connection between a digital and physical asset, facilitated through the tagging of a material or component as explored in B. Byers et al. (2022) would be desirable. But there are valid practical considerations such as discussed by iov42-leadership, including the impossibility of guaranteeing the tag will last as long as its carrier (01_iov42, 2024). For this reason, both participants of case-study two report the collaboration of iov42 with their partners on solutions such as isotope testing or nano technology (01_iov42, 2024; 02_iov42, 2024).

Ultimately, the question remains: how can *steel beam x*, purchased as part of a large batch i.e. for an area development, be identified among 10.000 very similar beams?

The beams could be physically identical, but their digital passport would be unique. In a truly circular built environment, in which the use cases described section 4.2.3 *BBMP Opportunities* were common practice, the certain identification of the correct physical asset to an existing digital record would have to be clear for multiple reasons: recording of maintenance activity, recording of abnormal events (i.e. fire, earthquake etc.), for deconstruction, sale, recertification, reuse, and many more.

A hardware-software ecosystem that could be imagined providing maximum transparency and accuracy could include the integration of BIM, BBMPs (i.e. stored on a material marketplace platform), and track-and-trace (T&T) technology attached to the physical asset, to reap the benefits of BBMPs for a circular economy in AEC.

5.6 Clash of Paradigms

In the creation of a circular economy in AEC, blockchain, as a technology designed to decentralize processes and place trust in the technology as opposed to people, fundamentally challenges the current socio-economic paradigm the construction sector operates in.

The interviews conducted throughout this research made clear that the adoption of BBMPs in AEC is not only a technical or economic question, but also one about social systems and how society wants to live together. This discussion is closely linked to the “Chicken & egg problem” described by practice and the question raised by one interviewee: “How do you create a market?”. Supporters of a governed, top-down, centralized system (stick approach) that would mandate the implementation of Material Passports and thus create a demand for them artificially is opposed by supporters of liberal, bottom-up, decentralized systems (carrot approach) that promote the idea the technology (Material Passports) must provide incentive schemes itself to naturally create demand, such as through the integration of blockchain technology. And crucially, the centralized system is the prevailing paradigm that the technology suggesting a decentralized approach to sharing, validating, and trading data and commodities wants to integrate into. This situation is what is at heart of the adoption-barriers of blockchain-based Material Passports (BBMPs) in AEC.

Having acknowledged this, iov42 has found a practical solution in adding central authorities, that conservative industries trust, to the node of networks for data validation processes and thus reaps the benefits of blockchain technology in terms of immutability, as well as the timestamping and notarization of transactions, without bypassing trusted authorities in the existing centralized paradigm.

5.7 Contributions to Academia & Practice

This research contributes to academia because it represents a valuable starting point for future research by synthesising previously studied aspects, studying early attempts at BBMPs in practice, and highlighting areas for future research by identifying opportunities and barriers of the adoption of BBMPs in AEC industry practice.

In addition, the execution of the research design and its methods revealed a pattern in the differences of how academia and practice approach the issue of BBMP-adoption, revealing a misalignment of academia and practice and suggesting a closer collaboration in tackling the adoption-barriers of BBMPs moving forward: BBMP-providers are focused on the interplay of market conditions and regulatory constraints (chicken & egg problem) as opposed to academia, which tends to focus on technical aspects of the integration of Material Passports and blockchain technology.

This research is also a contribution to practice by helping practitioners understand the various opportunities that lie in the digital and circular transition in general, and the opportunities of BBMP-adoption in particular. Additionally, BBMP-providers will benefit from this research as it may help them understand adoption issues they experience and identify areas of development with high reward but low risk. Material Passport-providers may find the research useful, as it provides insights that can inform their future decision making in business strategies and motivate product development.

Lawmakers benefit from gaining an understanding of the implications of the current status-quo of policies on the potential for the development of BBMPs; only then can regulators try to reform prevailing standard modes of operation for a circular transformation. Developers, architects, and contractors are among the AEC practitioners who will find innovative ideas in the research that might help them prepare for an ever-evolving digital and circular transition. And lastly, this research helps investors realize the economic potential of the digital and circular transition in AEC, specifically of integrating blockchain and Material Passports.

In conclusion, this study aims to close the gap between theoretical understanding and real-world implementations by including a wide range of stakeholders in the AEC industry. Despite the limited cases available for examination, there is distinct value in the identification, description, and categorization of opportunities for BBMPs and the barriers associated with their industry-wide adoption, providing a crucial basis for future research and development.

5.8 Limitations & Recommendations

Like any research, this study is subject to several limitations that could impact its outcome, including possible limitations to research design, methods, and data analysis.

The qualitative research approach generally bears the limitation of a lack of reproducibility because of its scope and the many uncontrollable variables that come with studying a phenomenon in its context (Blaikie & Priest, 2019). In addition, the subjectiveness of the researcher's interpretation has an impact on data analysis. Therefore, it is crucial to follow a clear structure in the execution of the chosen methods (Yin, 2009).

Several steps were taken to mitigate the potential of adverse effects of these limitations and improve the reliability of the research findings. On the one hand, expert- and case-study interviews followed a standardized approach, ensuring uniformity in data collection and minimizing response variability. On the other, several iteration rounds were used to carefully carry out the coding process, reducing subjectivity and improving consistency of data analysis.

Further, executed research methods could also include limitations, such as in the quality of the desk research, potentially overlooking relevant literature and practice content, as well as the sample size for semi-structured interviews, providing a limited basis for data collection.

Nevertheless, steps were undertaken to ensure the robustness and validity of findings in both cases. In an initial step, a structured approach to the selection of relevant literature was chosen to set boundaries for chapter 2 *Theoretical Background*, resulting in a shortlist of recently published articles covering the fundamental concepts of this research and their overlap as a starting point. Snowball sampling was then used to methodically include new material as the study progressed and deeper insights were discussed. Regarding interviews, despite time constraints, the research design was finalized as early as possible to maximize the possibilities for interview scheduling, and their semi-structured design served to optimize the quality and depth of the data gathered. Future research should consider a wider scope and larger sample size to improve the validity and generalizability of findings.

The researchers' prejudice and personal interests could also have induced bias into findings, as well as the limited experience with conducting interviews may fail to acknowledge and explore deeper reflections (Bryman, 2016). To mitigate this, interviews were meticulously prepared, an initial standard section of questions created a foundation after which interviewees were left the freedom to express themselves with limited guidance.

As BlockMaterials and iov42 are the only two available cases matching the topic and scope of this research, there are possible limitations to the quantity and quality of cases studied, potentially limiting the generalizations drawn from them (Blaikie & Priest, 2019). This suggests the re-examination of this research in a few years' time, once the market has seen higher levels of adoption of BBMP-solutions.

Lastly, it should be noted that the quantity of mentioned codes does not correspond with their quality. Knowing this, the analysis of findings only names quantities of mentioned codes without weighing findings. To also validate and prioritize research outcomes, a third method such as a focus group discussion with experts in the field of Material Passports and blockchain technology would have to be added to the research design.

5.9 Data Management & Ethical Considerations

Research that involves human research subjects for data collection necessitates the careful and responsible treatment of their personal data. As such, this thesis is subject to the human research ethics and data management procedures stipulated by the University of Technology Delft, in

accordance with the FAIR principles: Findable, Accessible, Interoperable, and Reusable (Wilkinson et al., 2016). Accordingly, a data management plan was drafted and can be accessed in *Appendix A*.

The data management plan is based on the type of data that was expected to be collected throughout this research, as well as how it was collected, processed, stored, and shared. All recordings that involved human participation was gathered only with consent of the participant.

Data ownership and management, storage locations, as well as the processing of sensitive personal information (SPI) and confidential business information (CBI) are further detailed in *Appendix A* and *Appendix B* (Interview Protocol).

6 Conclusion

The primary objective of this research was to investigate the opportunities blockchain-based Material Passports (BBMPs) present for the circular transition in AEC, as well as identifying and understanding the barriers that prevent their adoption into practice. The adoption of BBMPs into AEC practice represents a complex socio-techno-economic phenomenon that can only be studied in its context (Yin, 2009). This led to the research design described in chapter 3 *Methodology*.

The research goal had three dimensions (Blaikie & Priest, 2019):

1. *exploration* and *description* of blockchain-based material passport (BBMP)-opportunities and their specific potential
2. *understanding* of adoption barriers for technology in AEC, specifically that of BBMPs
3. *intervention* of the contemporary digital technology-adoption paradigm in AEC, as encountered by BBMPs, through the presentation of their inherent potential and a comprehensive list of their adoption barriers

This chapter summarizes the answers to the sub questions and the main research question.

6.1 Sub Question 1 – Material Passport Barriers

SQ1: What are barriers to Material Passports?

Barriers to the adoption of Material Passports in AEC emerged from literature and method one, semi-structured interviews, divided into two contributors: barriers for the adoption of digital technology in AEC in general, and barriers for Material Passports specifically.

The answer to sub question one is a list of AEC-general adoption barriers, summarized in *Table 22*, as well as a list of Material Passport-adoption barriers, summarized in *Table 23*.

Table 22 AEC-general adoption barriers for Material Passports in AEC

PESTLE	Barrier	Subcategories
Political	Adverse economic-political context	Economy maturity
		National context - information accessibility
		National context – political system
Economical	Chicken & egg problem	Regulation or market incentives?
	Industry fragmentation	Numerous SMEs competing in a highly diversified market without dominant players
	Market-competitiveness	Slim margins Lack of time General inefficiency of industry
Social	Change resistance	Lack of financial incentives
		Lack of vision
		Lack of time
		Technology resistance
		Fear of the new
Technological	Lack of digitalization & technology literacy	Lack of technology infrastructure
		Lack of technology literacy & human error in application of technology
Legal	-	
Environmental	-	

Table 23 Material Passport-specific adoption barriers for Material Passports in AEC

PESTLE	Barrier	Subcategories
Political	-	
Economical	Lack of financial incentives	Not sharing data = profitable in current economic paradigm
		Current MP-inherent value limited to marketing value (certification etc.)
		High upfront costs (data collection, data validation, data certification)
Social	-	
Technological	Inadequate information provision	Lack of information availability & data maturity
		Reluctance to input data: fear of sharing trade secrets
		Human error in data-input
		Data-input verification (enforcement-barrier)
	Lack of knowledge	Lack of awareness for CE + need for information accessibility
		Lack of awareness for value of building and material data
	Technical practicalities	Digital storage & modelling issues
		Interoperability complexity) - in between systems/digital technology
		Interoperability (complexity) - physical-digital asset connectivity
	Technology readiness	Lack of technology dissemination
		Lack of cases as proof of concept, demonstrating viable use cases
		Lack of systemic approach
	Legal	Regulatory frameworks
Lack of MP-standardization (content)		
Lack of MP-standardization (data formats)		
Lack of MP-standardization (costs for data-provision/collection)		
Connected legislation		
Environmental	-	

A detailed description of these findings can be found in section 4.1.1 *AEC-general Barriers*, and section 4.1.2 *Material Passport-specific Barriers*.

6.2 Sub Question 2 – Blockchain Barriers

SQ2: What are barriers to blockchain technology in AEC?

The answer to sub question two is a list of barriers blockchain technology is facing in its adoption into the AEC sector, summarized in *Table 24*. These are also presented in section 4.1.3 *Blockchain-specific Barriers*.

Table 24 Blockchain-specific adoption barriers in AEC

PESTLE	Barrier	Subcategories
Political	-	
Economical	-	
Social	Lack of trust & general scepticism	Bad reputation
		Fear of misuse/abuse of data (PII/IP)
		Fear of job displacement
		Technology resistance
Technological	Lack of knowledge	Don't understand it → aversion/scepticism
		Don't see necessity
	Technical practicalities	Interoperability (complexity) - in between systems/data protocols
		Interoperability (complexity) - blockchain-environment
		Ostrom principles
	Technology readiness	Technical feasibility without blockchain
		Lack of technology dissemination & viable use cases demonstrating proof of concept
		Lack of systemic approach
Legal	Regulatory frameworks	Lack of supporting regulation = passive barrier
		Legal concepts actively inhibiting blockchain adoption
Environmental	Environmental impact	Energy consumption of computing necessary for token mining

The findings from sub question one and two were synthesised to develop the coding schema for the analysis of method two: comparative case study analysis.

6.3 Sub Question 3 – BBMP Opportunities

SQ3: What opportunities do BBMP-providers see in the application of their technology?

The findings from the comparative case-study analysis reveal a shortlist of nine BBMP-opportunities as described by early providers of BBMPs in form of use cases for the implementation of their product, summarized in *Table 25*. Their detailed description can be found in section 4.2.3 *BBMP Opportunities*.

Table 25 Compiled list of BBMP-opportunities

BBMP-opportunities	Description
Facilitating future contracts for material reuse	Awarding unique identities to materials through the adoption of BBMPs enables the transfer of ownership of a material before delivering the physical asset.
Material marketplaces	Online platforms facilitating the trade of registered secondary materials, similar to eBay.
Active material stock trade	Active trading of ownership rights to materials bound in buildings, making real estate investment accessible and generating additional cash flow through trading fees.
PaaS (Products-as-a-Service)	Facilitated through track-and-trace (T&T) based on BBMPs, manufacturers retain ownership of materials in buildings and lease them to the developer.
Full asset tracking throughout material life cycle	Track-and-trace (T&T) of assets along their supply chain with potential for full lifecycle tracking facilitated by fundamental properties of blockchain technology and Material Passport-integration.
Residual material value transparency	Registering building materials makes residual value transparent, lowering project financing costs for asset owners.
Premiums for product transparency	Manufacturers will charge market premiums for transparent material provenance data, compensating investments for data collection.
Life cycle assessment (LCA)	LCAs based on building inventory for regulatory compliance.
Regulatory compliance	Blockchain provides “single layer of truth” for reporting, making Material Passports auditable and facilitating regularoty compliance.

In conclusion, it can be said that some opportunities outline scenarios that are very much linked to current BBMP-providers’ use cases and the respective benefits for their clients today, while others outline a comprehensive future ecosystem of interlinked dynamics that participants of this study suggest will be enabled through the adoption of BBMPs. This provides a comprehensive overview of opportunities of BBMP-adoption within their greater socio-techno-economic context in AEC practice, in form of relevant use cases.

6.4 Sub Question 4 – BBMP Adoption Barriers

SQ4: What are challenges that current and early attempts at BBMPs face?

The findings from the comparative case-study analysis also reveal a list of 14 BBMP-adoption barriers, developed using the PESTLE framework of analysis to ensure that none were overlooked. These findings, described in detail in section 4.2.4 *BBMP Adoption Barriers*, offer new insights into the field of blockchain-based Material Passports as a first assessment of the barriers that relevant BBMP-use cases face in their adoption into practice.

Table 26 presents the final list of BBMP-adoption barriers, structured according to the PESTLE framework of analysis.

Table 26 Compiled BBMP-adoption barriers

PESTLE	BBMP-adoption barrier
Political	Adverse economic-political context
Economical	Chicken & egg problem
	Industry fragmentation (AEC-industry)
	Lack of financial incentives (BBMPs)
	Market-competitiveness (AEC-industry)
Social	Lack of trust & general scepticism (blockchain)
	Change resistance (AEC-industry)
Technological	Inadequate information provision (BBMPs)
	Lack of knowledge (CE & MPs/ blockchain)
	Lack of digitalization & technology literacy
	Technical practicalities (BBMPs)
	Technology readiness (BBMPs)
Legal	Regulatory frameworks (BBMPs)
Environmental	Environmental impact (blockchain)

From the comparative case-study analysis, several conclusions can be drawn. Technological and economic constraints, such as a lack of digitalization and technology literacy, and a lack of financial incentives for BBMP-adoption are unanimous to the cases, as well as the emphasis on regulatory frameworks as active or passive barriers, including the necessity for standards to foster interoperability. However, there are also differences in experienced barriers, depending on the maturity of the BBMP-solution. Case-study one for example prioritizes conceptual discussions about economic and regulatory constraints such as a lack of necessary investments and a lack of “scale and scope”, whereas case-study two reports barriers in the interaction of users with their system, either concerning data input, or misconceptions about the underlying concepts of it. These differences, however, together form a concise list in relevant BBMP-adoption barriers.

6.5 Main Research Question – BBMP potential

Finally, the research design and the execution of its methods was able to answer the main research question:

What is the potential for integrating blockchain-based Material Passports (BBMPs) into practice?

Dividing potential into opportunities and challenges, the aim was to explore the opportunities of BBMP integration into AEC-industry practice, as well as the barriers that impede their adoption. The opportunities of BBMP adoption were examined by studying two distinct case-studies of early BBMP-providers and the use cases they describe for their BBMP-solutions. Barriers to the adoption of BBMPs first emerged from the review of existing literature, serving as a basis for data collection. After being mapped on the PESTLE framework of analysis, these barriers were studied by interviewing experts from academia and practice as well as through the comparison of barriers to the use cases described in the case-studies.

This research revealed significant potential for the integration of BBMPs into practice by balancing the benefits of described use cases with the significant barriers faced in their implementation. Apart from a positive environmental impact by encouraging circular strategies such as material recovery and reuse, BBMPs could have considerable economic potential, summarized in *Table 25*. By awarding materials unique identities (so-called “property rights”), BBMPs have the potential to facilitate future

contracts for material reuse and enable the transfer of their ownership prior to actual delivery. Next to secondary material marketplaces, this could make active material stock trade or “fluid asset” trading possible, increasing accessibility to real estate investments and providing additional monetization through trading fees. Moreover, BBMPs enable the complete track-and-trace of assets over the course of a materials lifecycle. Asset tracking and property rights also provide the potential to enable novel business and ownership models such as the servitization of materials and components through Products-as-a-Service (PaaS), in which developers lease the materials from manufacturers instead of purchasing them. And finally, the auditability provided by blockchains ‘single layer of truth’ paired with Life Cycle Assessment (LCA), made possible by the digital registration of materials in form of Material Passports, could guarantee regulatory compliance, improve residual material value transparency, and subsequently reduce project financing costs.

However, this research also revealed several barriers for the adoption of these described use cases and opportunities, across political, economical, social, technological, legal, and environmental factors. Political barriers to the implementation of BBMPs describe the economic-political environment of a particular national context, which might have an impact on information accessibility and economy maturity. Economic barriers include general AEC industry-specific characteristics such as its fragmentation and unique market-competitiveness including slim profit margins. These are compounded by a lack of financial incentives such as high upfront costs for data collection and technology implementation. Socially, the traditional AEC sector, known for its lethargic embrace of new technologies, is sceptical of blockchain and lacks faith in the value it proposes. This can be traced back to a lack of knowledge for the underlying concepts of the technology and a generally low level of technology literacy in AEC, which are part of technological barriers to BBMP-adoption. These further include inadequate information provision due to inaccessibility of data, lack of interoperability of systems, human error in data input and operation of technological systems, the reluctance to input data, as well as the impossibility to verify data. Additional challenges present technical practicalities such as data storage and modelling issues, as well as the challenge of designing appropriate blockchain networks regarding roles and responsibilities of nodes. BBMP-use cases and their benefits are also significantly challenged by a current lack of a systemic approach, involving politics, regulation, and practice, and an absence of viable use cases demonstrating their proof of concept. Importantly, regulatory frameworks fail to encourage BBMP-adoption, in some regards even actively prohibiting their implementation. And lastly, BBMPs need to reduce the environmental impact of blockchain technology to not jeopardize their potential environmental added value.

In conclusion, for the AEC sector to collectively reap the benefits of the considerable potential with BBMPs promise, specifically for the sectors transition towards a circular economy, the various, multifaceted and highly interlinked barriers that stand in the way of their adoption will have to be overcome, necessitating concerted efforts in the fields of politics, business, education, technology, and law.

6.6 Recommendations for Future Research

The presentation of the findings of this research, as well as their discussion reveals many possible areas for future research. A few of them are shortly summarized in the following section.

First, the findings of this study could be substantiated by a larger sample given the exploratory nature of this research, especially in a few years’ time when the technology has seen wider adoption, and more stakeholders can report on their experiences.

This research also provides a comprehensive basis for the future exploration of relevant and actionable enablers for the adoption of BBMPs into AEC practice.

Further, research could explore the intricacies of mentioned BBMP-use cases further such as the integration of secondary material marketplaces and BIM, or the impact of “fluid asset” trading as discussed in section 5.3 *Active Material Stock Trade (“Fluid asset” Trading)* on the operation of an asset managed by a housing association, or its impact on project financing costs. Additional research will also have to go into solving tagging issues of components and the complementary effects of integrating multiple passport documents.

7 Reflection

The final reflection on this research as a product, its relation to the study programme “MBE”, its process, and its planning, including a personal note, is attached to this report in *Appendix K*.

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9 Appendix

- A. Data management plan
- B. Interview protocol
- C. Madaster-MP
- D. Madaster-MP description
- E. Barriers Semi-structured Interviews
- F. BBMP Opportunities
- G. Barriers Comparative Case-study Analysis
- H. Cirdax-MP
- I. Iov42-MP description
- J. Blockchain description
- K. Reflection

Appendix A

Plan Overview

A Data Management Plan created using DMPonline

Title: Integrating blockchain-based material passports (BBMPs) into practice for a circular built environment - a closer look at opportunities and challenges.

Creator: Caspar von Bodelschwingh

Principal Investigator: Caspar von Bodelschwingh

Contributor: Brandon S. Byers, Ir. Dr. Sultan Çetin, Dr. Daniel M. Hall

Affiliation: Delft University of Technology

Template: TU Delft Data Management Plan template (2021)

ORCID ID: 0009-0006-7925-6093

Project abstract:

Recently, the academic community has acknowledged the theoretical potential for promoting circularity in the construction industry through the integration of blockchain technology and Material Passports (MPs). Yet, this potential remains mostly untapped in practice, contributing to a significant gap between theoretical frameworks and practical applications. This study therefore intends to explore the potential within blockchain-based Material Passports (BBMPs) by identifying their opportunities and the barriers impeding their adoption into AEC-practice. Based on a comprehensive literature and practice review exploring the underlying concepts of MPs and blockchain technology, the study investigates the potential of MPs in AEC, discusses unresolved issues, as well as their respective solutions as proposed by the integration of blockchain technology. The principal methods for gathering data in the first phase of this research are semi-structured interviews followed by a comparative case-study analysis of two early attempts at commercial BBMP-solutions. The PESTLE framework of analysis served as the primary method of analysis to identify relevant BBMP-adoption barriers as input for the comparative case-study analysis. The examined cases revealed a list of relevant use cases for BBMPs as well as a final list of barriers for their adoption into industry practice. Aimed at a wide audience, this research contributes to academia and practice by identifying and compiling the potential of BBMPs as well as their adoption barriers, which can serve as a comprehensive basis for further research.

ID: 141947

Start date: 29-01-2024

End date: 27-05-2024

Last modified: 24-06-2024

Integrating blockchain-based material passports (BBMPs) into practice for a circular built environment - a closer look at opportunities and challenges.

0. Administrative questions

1. Name of data management support staff consulted during the preparation of this plan.

My faculty data steward, Janine Strandberg, has reviewed this DMP on 18.03.2024.

2. Date of consultation with support staff.

2024-03-18

I. Data description and collection or re-use of existing data

3. Provide a general description of the type of data you will be working with, including any re-used data:

Type of data	File format(s)	How will data be collected (for re-used data: source and terms of use)?	Purpose of processing	Storage location	Who will have access to the data
Audio recordings of interviews	.mp4	Interviews are conducted online and recorded through MS Teams meeting, signed in by TU Delft account; recordings are deleted after transcription	Exploration and description of BBMPs use cases, understanding of adoption barriers and enablers for technology in AEC, specifically that of BBMPs	TU Delft drive (temporary storage)	Project team (Caspar von Bodelschwingh + Daniel Hall & Sultan Çetin)
Interview transcripts	.docx & .pdf	Automatic audio transcripts through MS Teams are edited to eliminate AI-transcription errors - participants are asked to review transcriptions before finalisation of transcripts; deleted after anonymisation	Temporary storage of expert interviews including Personally Identifiable Information (PII) of interviewees for easier processing and analysis before anonymising transcripts and deleting transcripts holding PII	TU Delft drive (temporary storage)	Project team (Caspar von Bodelschwingh + Daniel Hall & Sultan Çetin)
Anonymised interview transcripts	.docx & .pdf	Anonymisation of all Personally Identifiable Information (PII) in original transcript for permanent documentation of data	Privacy-preserving data on BBMP use cases and the barriers and enablers of their adoption in practice	TU Delft drive	Project team (Caspar von Bodelschwingh + Daniel Hall & Sultan Çetin)
ATLAS.ti Project File with coded interview transcripts	.atljproj23	Import of audio transcripts of expert interview recordings	Coding of interview transcripts to map relevant BBMP use cases as well as adoption barriers and enablers for technology in AEC, specifically that of BBMPs	TU Delft drive	Project team (Caspar von Bodelschwingh + Daniel Hall & Sultan Çetin)
Personally Identifiable Information (PII); participants' name, email, name of organisation, position, mobile number	.pdf & .xlsx	Contact information for participants taking part in interviews, case studies, and focus group discussions, received from web-search & professional network; not published	Administrative purposes: obtaining informed consent & communicating with potential participants (documenting inquiry process)	TU Delft drive (temporary storage)	Project team (Caspar von Bodelschwingh + Daniel Hall & Sultan Çetin)
Audio recordings of interviews conducted for comparative case study analysis	.mp4	Interviews are conducted online and recorded through MS Teams meeting, signed in by TU Delft account; recordings are deleted after transcription	Validation of findings from literature review and expert interviews	TU Delft drive (temporary storage)	Project team (Caspar von Bodelschwingh + Daniel Hall & Sultan Çetin)
Interview transcripts (comparative case study analysis)	.docx & .pdf	Automatic audio transcripts through MS Teams are edited to eliminate AI-transcription errors - participants are asked to review transcriptions before finalisation of transcripts; deleted after anonymisation	Temporary storage of case study interviews including Personally Identifiable Information (PII) of interviewees for easier processing and analysis before anonymising transcripts and deleting transcripts holding PII	TU Delft drive (temporary storage)	Project team (Caspar von Bodelschwingh + Daniel Hall & Sultan Çetin)
Anonymised interview transcripts (comparative case study analysis)	.docx & .pdf	Anonymisation of all Personally Identifiable Information (PII) in original transcript for permanent documentation of data	Privacy-preserving data on implemented BBMP use cases and barriers and enablers of their adoption in practice	TU Delft drive	Project team (Caspar von Bodelschwingh + Daniel Hall & Sultan Çetin)
ATLAS.ti Project File with coded interview transcripts (comparative case study analysis)	.atljproj23	Import of audio transcripts of case study interview recordings	Coding of interview transcripts to map findings from comparative case study analysis: BBMP use cases & their respective adoption barriers and enablers in practice	TU Delft drive	Project team (Caspar von Bodelschwingh + Daniel Hall & Sultan Çetin)
Thesis	.pdf	Record of research process as well as documentation and presentation of findings	Long-term documentation	TU Delft drive	Project team (Caspar von Bodelschwingh + Daniel Hall & Sultan Çetin)

I requested a TUDelft Project Data Storage (U:) registered with the number C240111898.

4. How much data storage will you require during the project lifetime?

- < 250 GB

II. Documentation and data quality

5. What documentation will accompany data?

- Data dictionary explaining the variables used
- Methodology of data collection

III. Storage and backup during research process

6. Where will the data (and code, if applicable) be stored and backed-up during the project lifetime?

- Project Storage at TU Delft
- OneDrive

In some cases, as specified in question 3., information will be temporarily stored in the TU Delft drive.

IV. Legal and ethical requirements, codes of conduct

7. Does your research involve human subjects or 3rd party datasets collected from human participants?

- Yes

8A. Will you work with personal data? (information about an identified or identifiable natural person)

If you are not sure which option to select, first ask you [Faculty Data Steward](#) for advice. You can also check with the [privacy website](#) . If you would like to contact the privacy team: privacy-tud@tudelft.nl, please bring your DMP.

- Yes

8B. Will you work with any other types of confidential or classified data or code as listed below? (tick all that apply)

If you are not sure which option to select, ask you [Faculty Data Steward](#) for advice.

- Yes, confidential data received from commercial, or other external partners

(Potentially, if comparative case study analysis is conducted and insight is given into company-internal data.)

9. How will ownership of the data and intellectual property rights to the data be managed?

For projects involving commercially-sensitive research or research involving third parties, seek advice of your [Faculty Contract Manager](#) when answering this question. If this is not the case, you can use the example below.

The datasets underlying the published papers will be publicly released following the TU Delft Research Data Framework Policy. During the active phase of research, the project leader from TU Delft will oversee the access rights to data (and other outputs), as well as any requests for access from external parties. They will be released publicly no later than at the time of publication of corresponding research papers.

10. Which personal data will you process? Tick all that apply

- Other types of personal data - please explain below
- Data collected in Informed Consent form (names and email addresses)
- Signed consent forms
- Email addresses and/or other addresses for digital communication
- Names and addresses

- Identity of institution/organisation
- Role within that institution/organisation

11. Please list the categories of data subjects

- MP providers
- BBMP providers
- Researchers
- Legal experts

12. Will you be sharing personal data with individuals/organisations outside of the EEA (European Economic Area)?

- No

15. What is the legal ground for personal data processing?

- Informed consent

16. Please describe the informed consent procedure you will follow:

All study participants will be asked for their written consent for taking part in the study and for data processing before the start of the interview.

17. Where will you store the signed consent forms?

- Same storage solutions as explained in question 6

18. Does the processing of the personal data result in a high risk to the data subjects?

If the processing of the personal data results in a high risk to the data subjects, it is required to perform [Data Protection Impact Assessment \(DPIA\)](#). In order to determine if there is a high risk for the data subjects, please check if

any of the options below that are applicable to the processing of the personal data during your research (check all that apply).

If two or more of the options listed below apply, you will have to [complete the DPIA](#). Please get in touch with the privacy team: privacy-tud@tudelft.nl to receive support with DPIA.

If only one of the options listed below applies, your project might need a DPIA. Please get in touch with the privacy team: privacy-tud@tudelft.nl to get advice as to whether DPIA is necessary.

If you have any additional comments, please add them in the box below.

- None of the above applies

Some participants will be asked to share information regarding their already commercially marketed BBMP solution, including decision making, business case strategies, and barriers they face (legal, economic, societal etc.). This may be of interest to those MP providers that haven't yet developed a blockchain-integrated solution.

Likewise, MP-providers will be asked about their decision-making behind having so far abstained from a blockchain-integration, which may touch on their current or future business strategies.

The risk to the data subjects could be considered low as only final research findings are publicly shared.

22. What will happen with personal research data after the end of the research project?

- Personal research data will be destroyed after the end of the research project

V. Data sharing and long-term preservation

27. Apart from personal data mentioned in question 22, will any other data be publicly shared?

- All validated non-positive results which do not contain personal data

The risk for re-identification is mitigated as only final research findings are publicly shared.

29. How will you share research data (and code), including the one mentioned in question 22?

- All pseudonymised data will be uploaded to 4TU.ResearchData with restricted access

Only final research findings will be publicly shared and uploaded to 4TU.ResearchData.

30. How much of your data will be shared in a research data repository?

- < 100 GB

31. When will the data (or code) be shared?

- At the end of the research project

32. Under what licence will be the data/code released?

- Other - Please explain

This is a Master's thesis - it will be published on the TU Delft Education repository. It doesn't need a license.

VI. Data management responsibilities and resources

33. Is TU Delft the lead institution for this project?

- Yes, the only institution involved

34. If you leave TU Delft (or are unavailable), who is going to be responsible for the data resulting from this project?

The Head of the Department of the Best Experiments (hod-bestexperiments@tudelft.nl)

35. What resources (for example financial and time) will be dedicated to data management and ensuring that data will be FAIR (Findable, Accessible, Interoperable, Re-usable)?

4TU.ResearchData is able to archive 1TB of data per researcher per year free of charge for all TU Delft researchers. We do not expect to exceed this and therefore there are no additional costs of long term preservation.

Planned Research Outputs

Text - "List of BBMP-adoption barriers"

Compiled list of adoption barriers for blockchain-based Material Passports (BBMPs) in the AEC sector.

Text - "List of blockchain-specific adoption barriers for Material Passports in AEC"

A list of identified adoption barriers of blockchain technology in AEC-practice.

Text - "List of Material Passport-specific adoption barriers for Material Passports in AEC"

A list of identified adoption barriers of Material Passports (MP), specific to the adoption issues faced by Material Passports in AEC-practice.

Text - "List of AEC-general adoption barriers for Material Passports in AEC"

A list of identified adoption barriers of Material Passports (MP), specific to the adoption issues faced by technology in AEC-practice in general.

Text - "Master's thesis report"

The final master's thesis report.

Text - "List of BBMP Opportunities"

A list of identified blockchain-based Material Passport (BBMP) opportunities in form of relevant use cases as reported by case-study participants.

Planned research output details

Title	Type	Anticipated release date	Initial access level	Intended repository(ies)	Anticipated file size	License	Metadata standard(s)	May contain sensitive data?	May contain PII?
List of BBMP-adoption barriers	Text	2024-07-01	Open	4TU.ResearchData science.engineering.design	1 MB	Creative Commons Attribution 4.0 International	None specified	No	No
List of blockchain-specific adoption barriers for ...	Text	2024-07-01	Open	4TU.ResearchData science.engineering.design	1 MB	Creative Commons Attribution 4.0 International	None specified	No	No
List of Material Passport-specific adoption barriers ...	Text	2024-07-01	Open	4TU.ResearchData science.engineering.design	1 MB	Creative Commons Attribution 4.0 International	None specified	No	No
List of AEC-general adoption barriers for Material ...	Text	2024-07-01	Open	4TU.ResearchData science.engineering.design	1 MB	Creative Commons Attribution 4.0 International	None specified	No	No
Master's thesis report	Text	2024-07-01	Open	4TU.ResearchData science.engineering.design	4 MB	Creative Commons Attribution 4.0 International	None specified	No	No
List of BBMP Opportunities	Text	2024-07-01	Open	4TU.ResearchData science.engineering.design	1 MB	Creative Commons Attribution 4.0 International	None specified	No	No

Appendix B

Integrating blockchain-based material passports (BBMPs) into practice for a circular built environment – a closer look at barriers and enablers.

Interview Protocol

The following interview protocol was developed by Caspar von Bodelschwingh for the purpose of conducting research as part of his Master's thesis in the track 'Management in the Built Environment' at the Faculty of Architecture at TU Delft.

Purpose of interview: This interview is being conducted as part of my Master's thesis titled "Integrating blockchain-based material passports (BBMPs) into practice for a circular built environment – a closer look at barriers and enablers.". My main goal of this research is to identify opportunities and barriers of the integration of blockchain-based Material Passports (BBMPs) into AEC industry practice. However, in this interview, I want to focus on *Material Passports (MPs) and the challenges they face in their application in practice, as well as possible solutions for these challenges as proposed by blockchain technology.*

Recently, the academic community has acknowledged the theoretical potential for promoting circularity in the construction industry through the integration of blockchain technology and Material Passports (MPs). Yet, this potential remains mostly untapped in practice, contributing to a significant gap between theoretical frameworks and practical applications. This study therefore intends to identify potential of the adoption of blockchain-based material passports (BBMPs) into practice to close this gap and fully capitalize on the benefits of BBMPs for the transition of the architecture, engineering, and construction (AEC) sector towards a circular economy (CE).

In the first phase of this research I will conduct semi-structured interviews, followed by a comparative case study analysis of commercial BBMP projects. The collected data is synthesised by analysing and mapping opportunities of BBMPs in form of use cases as well as the barriers for their integration into AEC-practice.

This interview, as part of the first phase of my research, is aiming to provide answers to the following research questions:

What is the potential of integrating blockchain-based Material Passports (BBMPs) into practice?

Sub question 1 – What are the barriers to Material Passports?

Sub question 2 – What are barriers to blockchain technology in AEC?

Sub question 3 – What opportunities do BBMP-providers see in the adoption of their technology?

Sub question 4 – What are challenges that current and early attempts at BBMPs face?

I have planned this interview to last no longer than 30 min. During this time, I want to cover several questions. If time begins to run short, it may be necessary to interrupt you in order to push ahead and complete this line of questioning.

Main questions:

How would you describe material passports (MPs)?

What, in your point of view, or from the point of view of your organisation, are MPs for?

Can you name a couple of potential use cases? How do current and future use cases differ?

How do you see MPs in relation to the concept of a circular economy (CE)?

From your experience, what barriers do you see in the adoption of MPs in practice?

What type of data do you store? Generic, or specific? How do you acquire data?

How do you ensure accuracy and reliability of information? Data gathering in design-, construction-, maintenance period? Data source & validation/credibility?

How do you ensure traceability of continuous data-updates on MPs throughout their life cycle?

How do you think about data standardization? Should MPs be regulated?

How do you treat data ownership and copyright? (à generic vs. specific data)

Have you considered the integration of your MP-product with any other digital technology?

What potential, in your opinion, does blockchain technology offer to MPs? How can blockchain technology help overcome some of the challenges of MPs, that you described before?

Given the mentioned characteristics/potential for MPs, what would you consider most important/impactful and why?

Have you as an organization ever considered blockchain technology as an infrastructure for MPs? If so, how exactly? If not, why not?

What do you think are current problems with the integration of blockchain and MPs? Why do you think BBMPs haven't materialized yet?

What do you think could be done to enable their adoption?

Can you imagine a use case for a Material Passport, in which blockchain integration is inevitable?

Can only automation solve 'garbage in, garbage out' problem? Or how can blockchain offer unquestionable validation procedure?

Can you elaborate on tokenization as incentive scheme?

Data is argued to be non-rival/collective good. Should material and component information be publicly available (i.ex. open-source MP-database)?

How should data ownership and copyright be treated? And how does the integration of MPs and blockchain technology influence that?

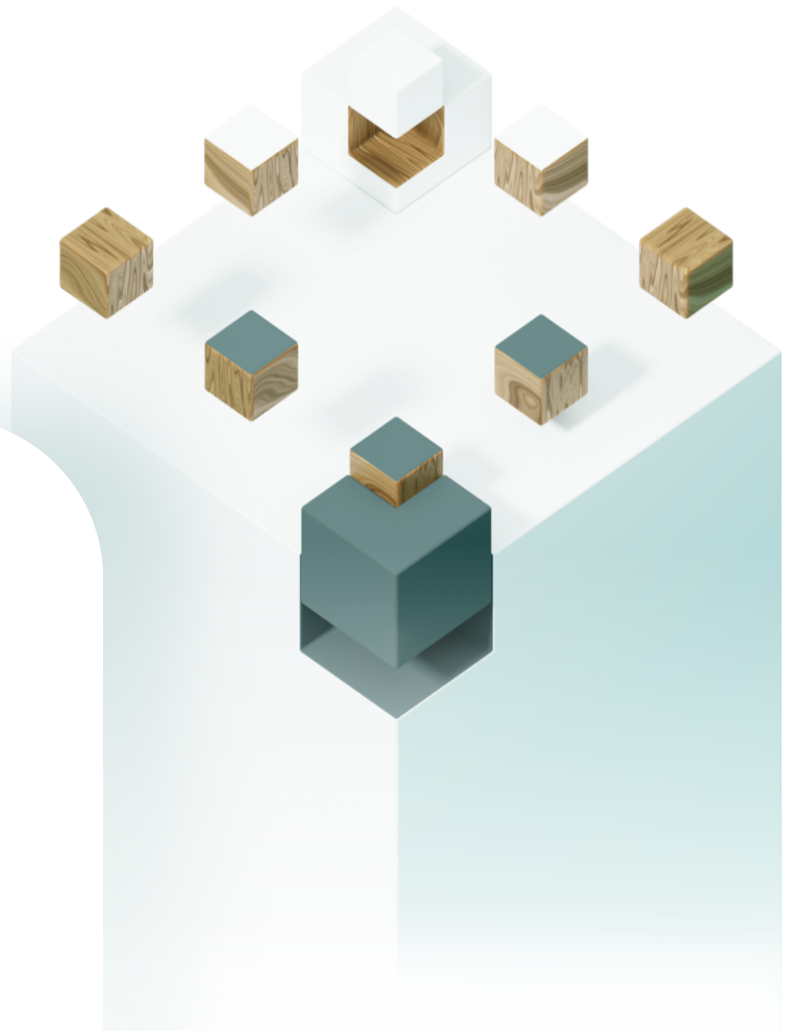
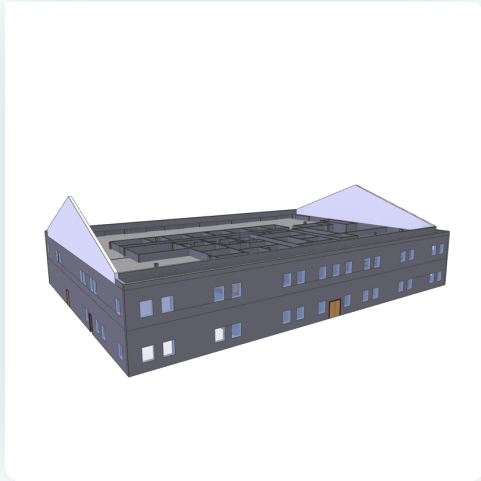
What do you think are the most important adoption barriers for blockchain-based MPs currently & moving forward?

What do you think could be done to enable their adoption? Regulation or incentivization?



Material passport

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PREPARED BY

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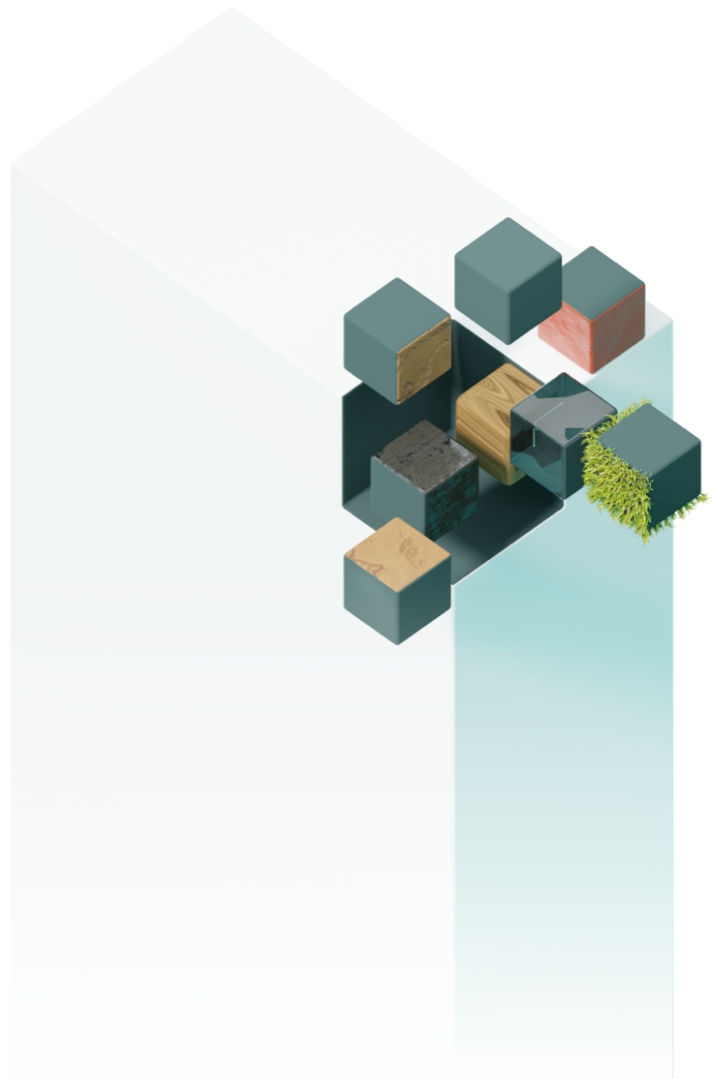
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4/11/2024



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General information

Building

NAME

Dorpsstraat 1

ADDRESS

Marsdijk 1
4043JW Opheusden
Netherlands

DELIVERY DATE

10/4/1926

GROSS SURFACE AREA

100000 m²

GROSS INTERNAL AREA

215 m²

BUILDING PHASE

Renovation

USAGE

Offices (Office < 1000m²)

Building owner

NAME

Lanckhorst N.V.

Rating schemes

BREEAM REGISTRATION NUMBER

1345

MPG-SCORE

0 €/m².year

Expected lifespan

BUILDING (YEARS)

50

STRUCTURE (YEARS)

50

SKIN (YEARS)

50

SERVICES (YEARS)

50

SPACE PLAN (YEARS)

50

STUFF (YEARS)

50

EXPECTED LIFESPAN SURROUNDINGS (YEARS)

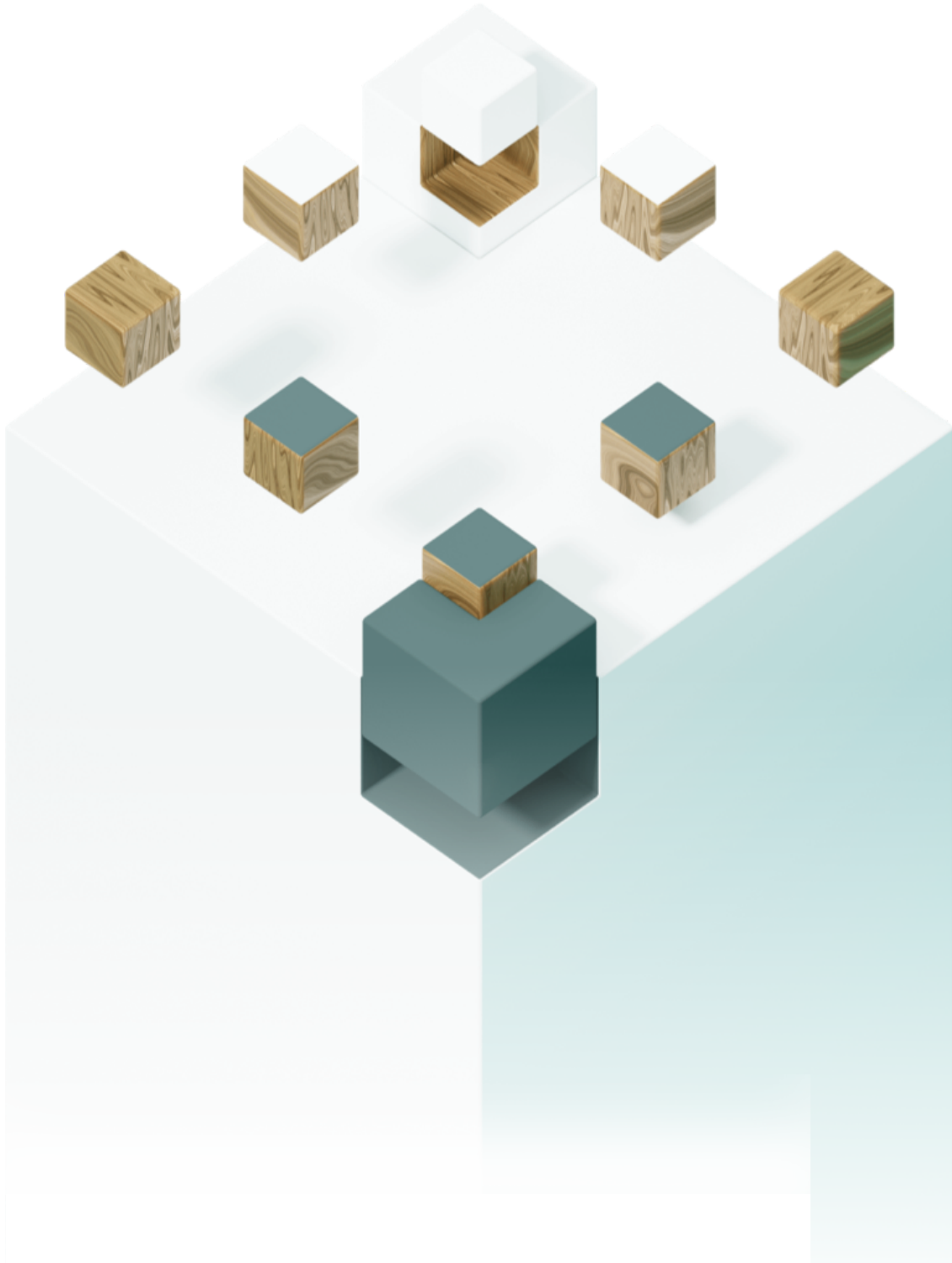
50



Material passport

Dorpsstraat 1

Source Information





Source Information

Sources

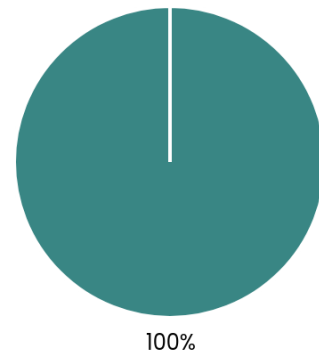
Madaster primarily uses IFC building files to calculate the material quantities. To do this, you must include the "base quantities" of the objects in the export. The objects must be assigned a material property, as well as a classification code. Madaster does not calculate quantities: all geometric information and all quantities are imported directly from the IFC model. On the Madaster Platform, the quality of the source files is displayed under "Source file quality". All calculations on the Madaster Platform are made within these frameworks. Consequently, any missing and/or incomplete and/or incorrect information in the source files immediately results in inaccurate results. Therefore, Madaster cannot warrant the quality of these results. As a secondary source of information, a Microsoft Excel file (based on a Madaster Excel template) can be imported containing geometric information about the building, information on the building parts and/or components, materials, as well as classification codes.

Active Source files

Name	Classification method	Date exported
Office_A_20110811.ifc	NL-SfB	8/11/2011

Applied Material and Product Databases

- EPEA Generic - BENELUX (100%)
- NMD Categorie 1 (0%)



Completeness of Source Information

819
(62.4%)

Elements unlinked

1313
(100%)

Elements with unknown layer

214
(16.3%)

Elements with insufficient geometry



Material passport

Dorpsstraat 1

Object in Detail





Mass

Total mass and mass/m² demonstrate the quantity and intensity of materials temporarily stored within the building. While mass cannot be eliminated, the goal is to use less materials to achieve the same goal.

Total Mass

67.69 t

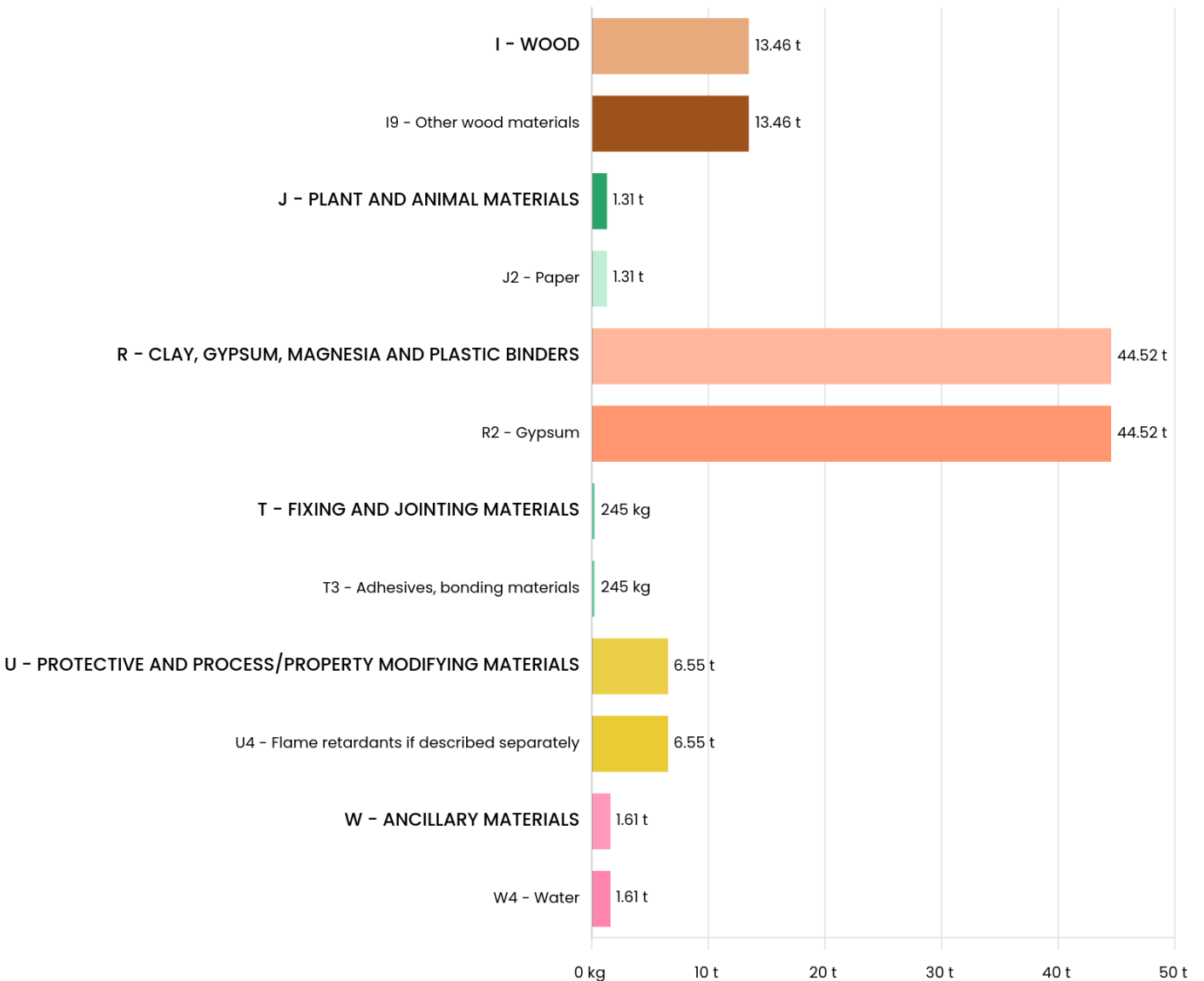
Material Intensity

677 g/m²

Construction Materials

The building is comprised of material subfamilies, grouped into the following material families.

Material families





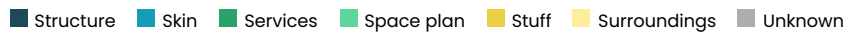
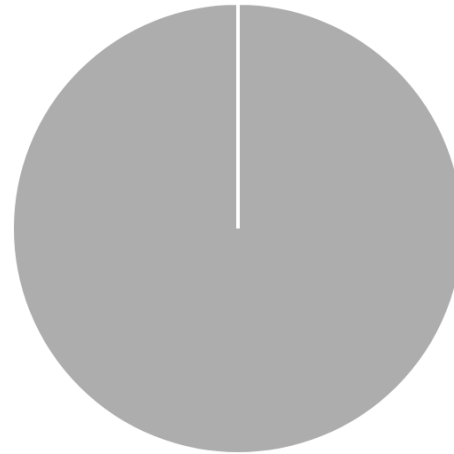
Mass by Shearing Layer

Shearing Layers

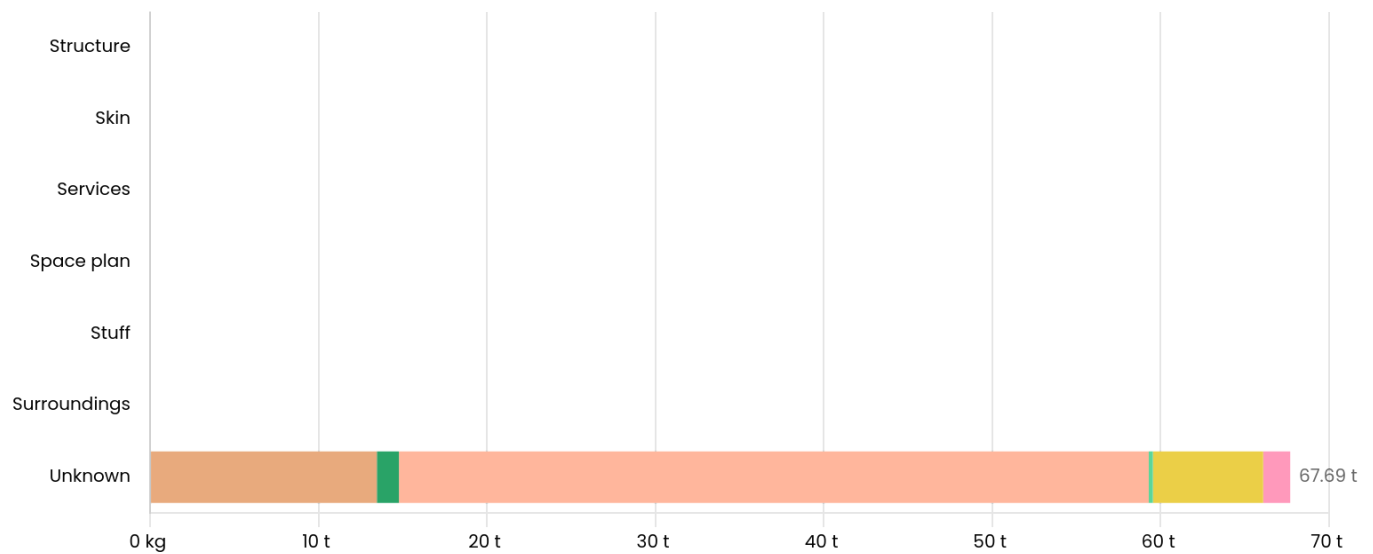
Madaster uses the "Shearing Layers" model [Duffy, Brand, 1994] to divide a building into 6 layers: Site, Structure, Skin, Services, Space Plan, and Stuff.

Material families

The 494 unique materials comprising the building have been grouped into 13 material families.



Layer Composition

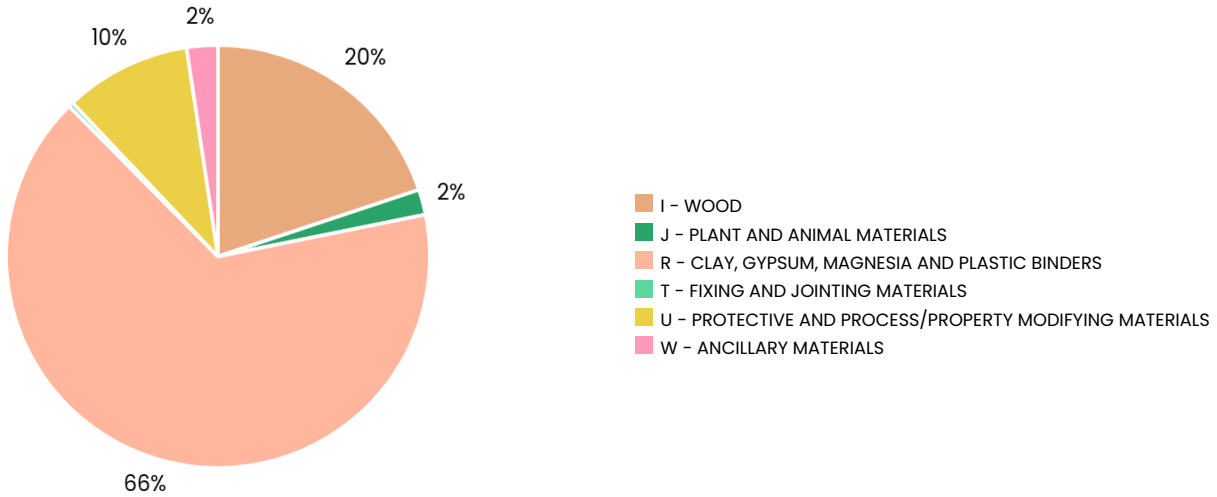


- I - WOOD
- J - PLANT AND ANIMAL MATERIALS
- R - CLAY, GYPSUM, MAGNESIA AND PLASTIC BINDERS
- T - FIXING AND JOINTING MATERIALS
- U - PROTECTIVE AND PROCESS/PROPERTY MODIFYING MATERIALS
- W - ANCILLARY MATERIALS

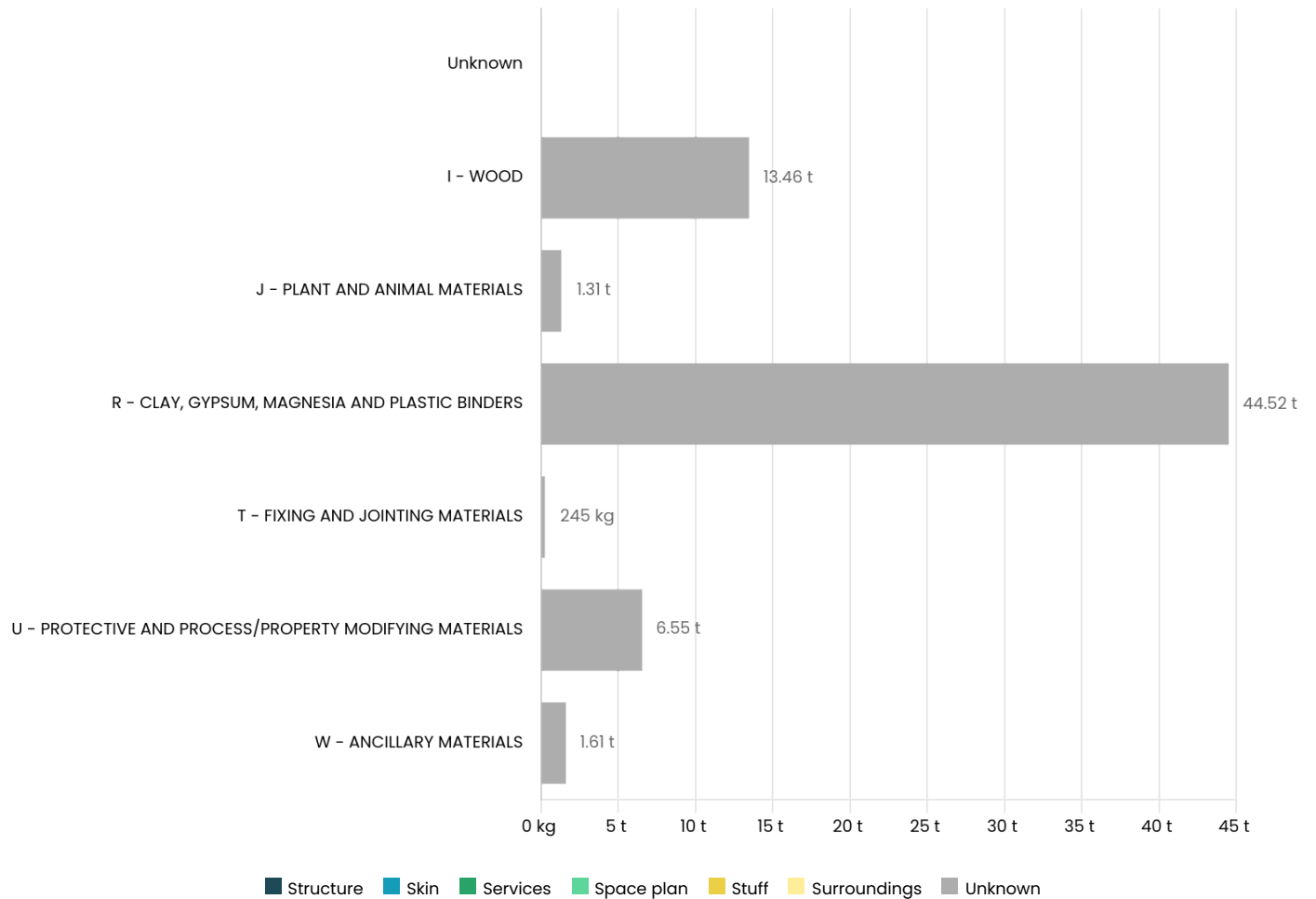


Mass by Material Families

Material families



Material Family Allocation Across Building Shearing Layers





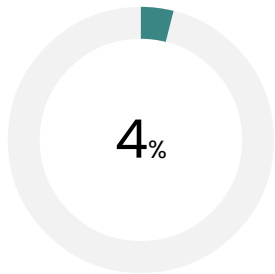
Mass details

Material family	Total	Structure	Skin	Services	Space plan	Stuff	Surroundings	Unknown
Unknown	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg
I - WOOD	19.9% 13.46 t	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	19.9% 13.46 t
I9 - Other wood materials	19.9% 13.46 t	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	19.9% 13.46 t
J - PLANT AND ANIMAL MATERIALS	1.9% 1.31 t	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	1.9% 1.31 t
J2 - Paper	1.9% 1.31 t	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	1.9% 1.31 t
R - CLAY, GYPSUM, MAGNESIA AND PLASTIC BINDERS	65.8% 44.52 t	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	65.8% 44.52 t
R2 - Gypsum	65.8% 44.52 t	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	65.8% 44.52 t
T - FIXING AND JOINTING MATERIALS	0.4% 245 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0.4% 245 kg
T3 - Adhesives, bonding materials	0.4% 245 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0.4% 245 kg
U - PROTECTIVE AND PROCESS/PROPERTY MODIFYING MATERIALS	9.7% 6.55 t	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	9.7% 6.55 t
U4 - Flame retardants if described separately	9.7% 6.55 t	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	9.7% 6.55 t
W - ANCILLARY MATERIALS	2.4% 1.61 t	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	2.4% 1.61 t
W4 - Water	2.4% 1.61 t	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	0% 0 kg	2.4% 1.61 t



Madaster Circularity Indicator (MCI)

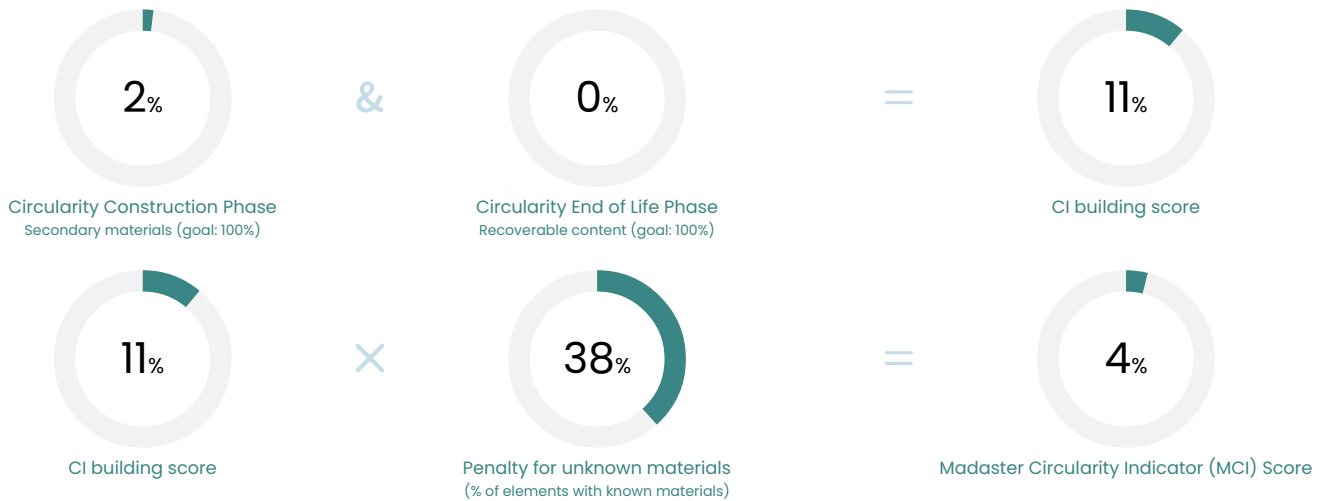
Circularity measures the degree of secondary materials used during construction, and potential for reuse & recycling at their end of use.



Madaster Circularity Indicator (MCI)

The Madaster Circularity Indicator (MCI) assesses the total circularity of a building based on three phases: 1) input in the construction process, 2) the utility during the use phase, and 3) the destination of the materials at the end-of-life phase. A building with a high score is constructed with reused and recycled materials and has a higher-than-average utility. A fully circular building has a score of 100%. The MCI is based on the Material Circularity Indicator that has been developed by the Ellen MacArthur Foundation. All rights reserved.

MCI Calculation Components



MCI by Shearing Layer

	Structure	Skin	Services	Space plan	Stuff	Surroundings	Unknown
Madaster Circularity Indicator (MCI) Score							4%
CI building score							11%
Score Subcomponents							
Circularity Construction Phase Secondary materials (goal: 100%)	-	-	-	-	-	-	2%
Circularity End of Life Phase Recoverable content (goal: 100%)	-	-	-	-	-	-	0%



Circularity Construction Phase

	Structure	Skin	Services	Space plan	Stuff	Surroundings	Unknown
Secondary materials (goal: 100%)	-	-	-	-	-	-	2% 1.31 t
Mass of product (t)	0 kg	0 kg	0 kg	0 kg	0 kg	0 kg	67.69 t
Mass Composition							
Applied recycled materials (% of mass)	-	-	-	-	-	-	2% 1.31 t
Applied renewables sustainably produced material (% of mass)	-	-	-	-	-	-	0% 0 kg
Applied reused components (% of mass)	-	-	-	-	-	-	0% 0 kg
Recycling							
Efficiency of recycling process for construction phase (%)	-	-	-	-	-	-	100%
Mass of waste generated during recycling process (t)	-	-	-	-	-	-	0 kg

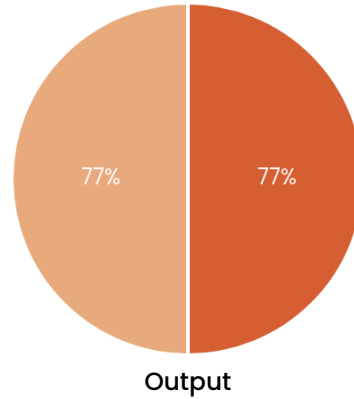
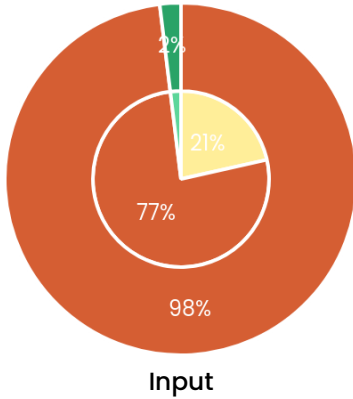
Circularity End-Of-Life Phase

	Structure	Skin	Services	Space plan	Stuff	Surroundings	Unknown
Recoverable content (goal: 100%)	-	-	-	-	-	-	0%
Mass of product (t)	0 kg	0 kg	0 kg	0 kg	0 kg	0 kg	67.69 t
Mass Composition							
Materials for recycling which are going to be collected (% of mass)	-	-	-	-	-	-	0% 0 kg
Components for reuse which are going to be collected (% of mass)	-	-	-	-	-	-	0% 0 kg
Mass of potential landfill & energy incineration (t)	-	-	-	-	-	-	67.69 t
Recycling							
Efficiency of recycling process for end of life phase (%)	-	-	-	-	-	-	100%
Mass of potential landfill & energy incineration of the recycling process (t)	-	-	-	-	-	-	0 kg



Feedstock Input & Output Flows

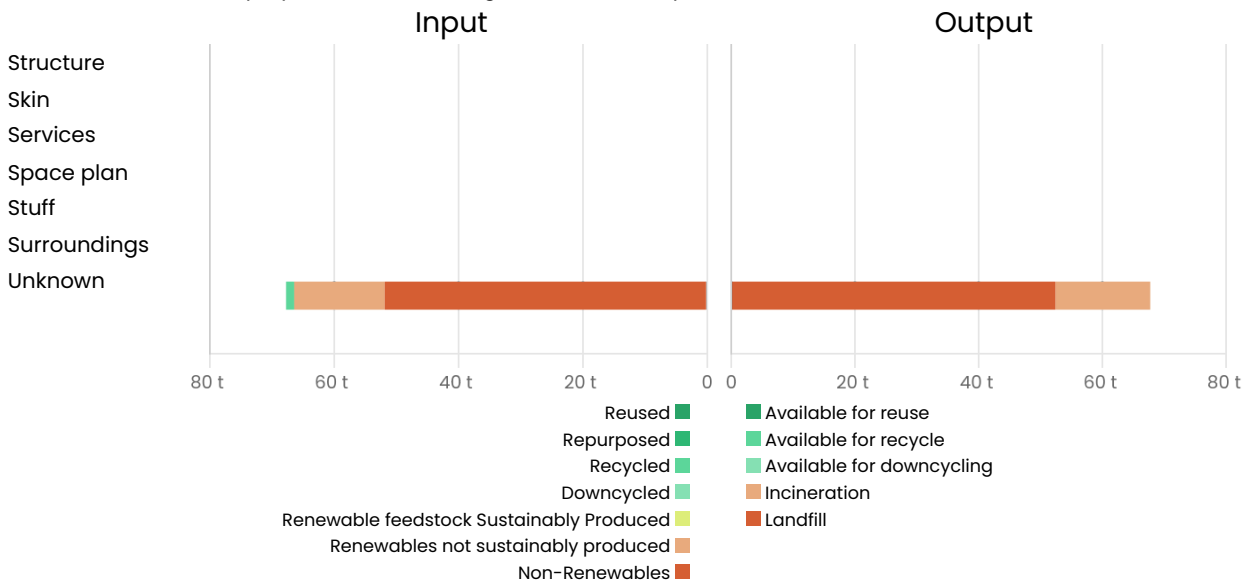
Material flows



Primary Feedstock	66.38 t	98.1%	Waste	67.69 t	100%
Renewables:	14.55 t	21.5%	Landfill:	52.37 t	77.4%
Renewable feedstock Sustainably Produced:	0 kg	0%	Incineration:	15.32 t	77.4%
Non-Renewables:	51.83 t	76.6%	Recoverable	0 kg	0%
Secondary	1.31 t	1.9%	Available for reuse:	0 kg	0%
Reused:	0 kg	0%	Available for recycle:	0 kg	0%
Repurposed:	0 kg	0%	Available for downcycling:	0 kg	0%
Recycled:	1.31 t	1.9%			
Downcycled:	0 kg	0%			

Input/Output flows by Shearing Layers

The feedstock view displays material sourcing and end-of-life potential.





Feedstock Input

	Structure	Skin	Services	Space plan	Stuff	Surroundings	Unknown
Mass of product (t)	0 kg	0 kg	0 kg	0 kg	0 kg	0 kg	67.69 t
Mass Composition							
Primary Feedstock	-	-	-	-	-	-	98% 66.38 t
Non-Renewables	-	-	-	-	-	-	77% 51.83 t
Renewables	-	-	-	-	-	-	21% 14.55 t
Renewable feedstock Sustainably Produced	-	-	-	-	-	-	0% 0 kg
Secondary	-	-	-	-	-	-	2% 1.31 t
Downcycled	-	-	-	-	-	-	0% 0 kg
Recycled	-	-	-	-	-	-	2% 1.31 t
Repurposed	-	-	-	-	-	-	0% 0 kg
Reused	-	-	-	-	-	-	0% 0 kg
Scarcity							
Physically scarce	-	-	-	-	-	-	0% 0 kg
Socioeconomic scarce	-	-	-	-	-	-	0% 0 kg

Feedstock Output

	Structure	Skin	Services	Space plan	Stuff	Surroundings	Unknown
Mass of product (t)	0 kg	0 kg	0 kg	0 kg	0 kg	0 kg	67.69 t
Mass Composition							
Available for reuse	-	-	-	-	-	-	0% 0 kg
Available for recycle	-	-	-	-	-	-	0% 0 kg
Available for downcycling	-	-	-	-	-	-	0% 0 kg
Incineration	-	-	-	-	-	-	77% 52.37 t
Landfill	-	-	-	-	-	-	23% 15.32 t



Material passport

Dorpsstraat 1

Environmental





Material passport

Dorpsstraat 1

Embodied Carbon (GWP)

The total environmental impact for A1-A3 (EN 15804).

Total

-16.28 t CO₂e

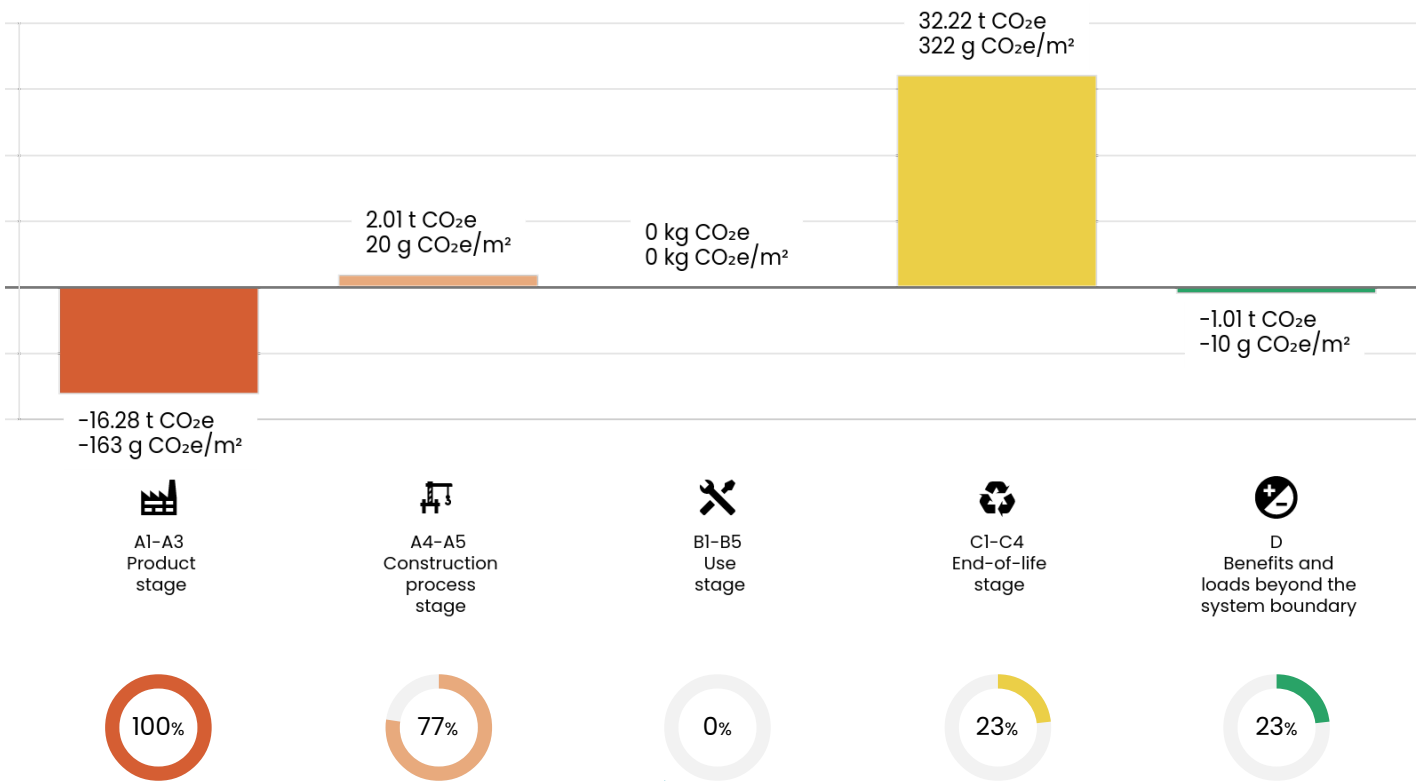
Per m²

-163 g CO₂e/m²

Life Cycle Assessment (LCA)

A Life Cycle Assessment (LCA) analyses the environmental impacts of a building during its lifecycle. A lifecycle is defined by the following phases: the production of construction products (A1-A3), the process of constructing a building on site (A4-A5), the use of the building (B1-B5), the disassembly of a building (C1-C4), and the potential to recycle a building after disassembly (D).

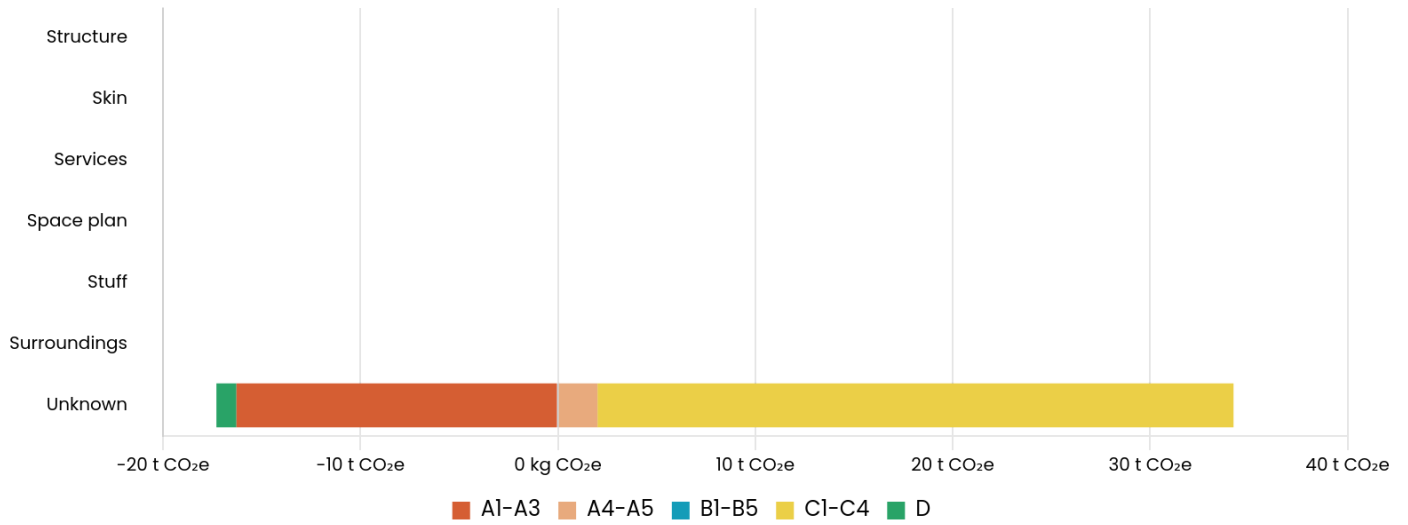
Embodied Carbon (GWP) across Lifecycle



% of known building mass with Embodied Carbon (GWP) data



Embodied Carbon (GWP) by Shearing Layers



	Structure	Skin	Services	Space plan	Stuff	Surroundings	Unknown
A1-A3	-	-	-	-	-	-	-16.28 t CO ₂ e
A4-A5	-	-	-	-	-	-	2.01 t CO ₂ e
B1-B5	-	-	-	-	-	-	-
C1-C4	-	-	-	-	-	-	32.22 t CO ₂ e
D	-	-	-	-	-	-	-1.01 t CO ₂ e



Material passport

Dorpsstraat 1

Financial





Material Value

Material value measures the present monetary value of materials, accounting for the costs of disassembly, transportation and processing for re-sale.

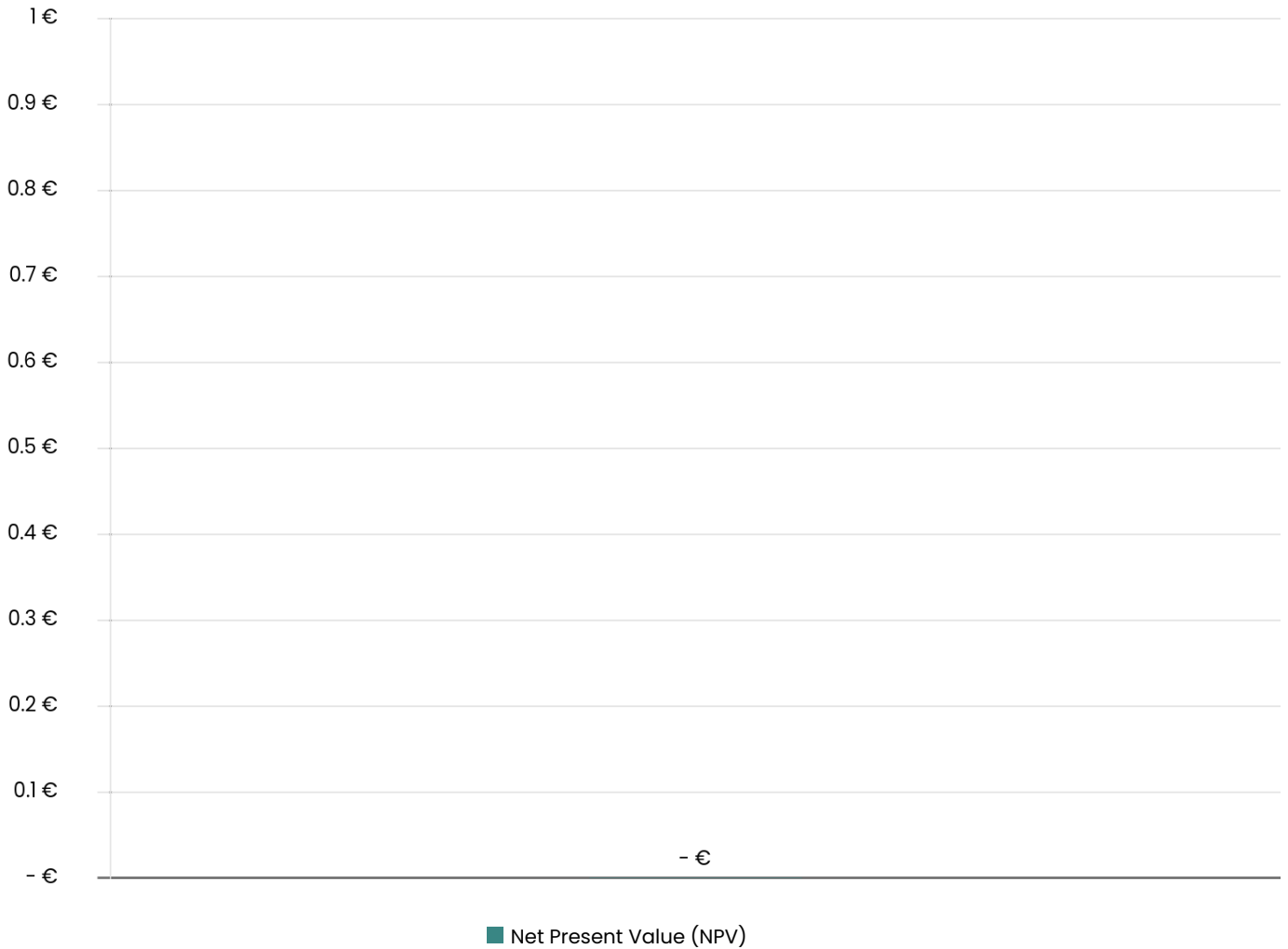
Net Present Value (NPV)

— €
- €/m²

Madaster Financial Module

The Madaster Financial module was developed to measure and optimize the residual value of buildings. The Madaster Financial Module visualizes the value of the materials and products at the time of construction and demolition.

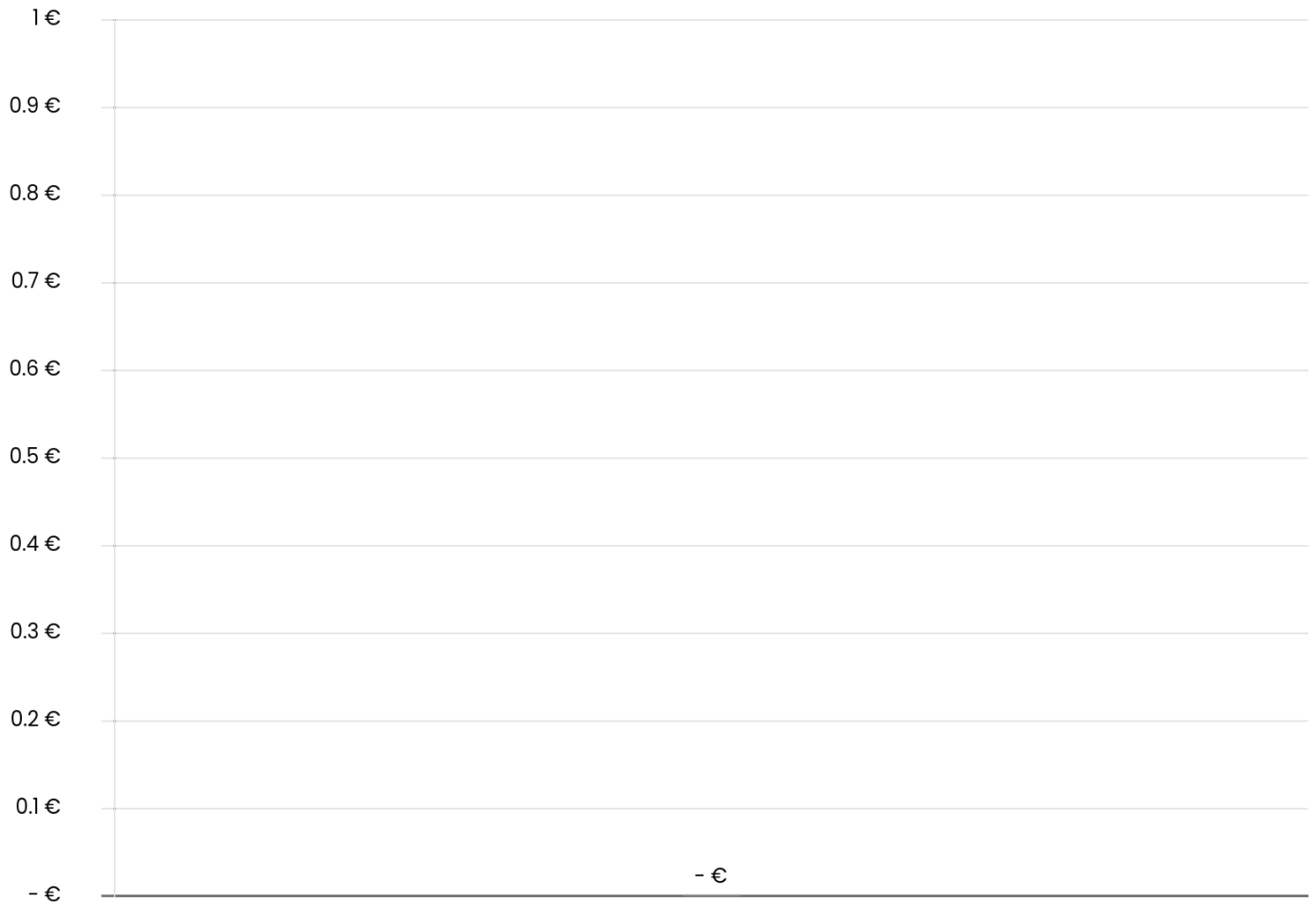
Material Value





Material Value

Material Value by Building Layer (End of Life)



	Total	Unknown
Expiration year cash flow	0	1976
NPV value end of life	€0	€0

Appendix D

Madaster-MP description & analysis

The Madaster platform digitally registers buildings in form of 3D-models (ideally BIM), uploaded by asset owners. Material properties and classification codes need to be assigned to every object or component in the BIM-model so they can be linked to databanks containing information about material composition, environmental impact etc. (Madaster Foundation, 2024). Responsibility for data completeness and correctness rests with the asset owner. The platform thus acts as a repository for static building and material information, cataloguing buildings with their materials and providing an inventory that includes information about their quality (i.e. primary/secondary materials), location, embodied carbon (CO₂-equivalent), and future reuse (recoverability). When a building is registered on Madaster, it is assigned a Material Passport that visualises this information, making it available to owners. This helps owners understand the circular value of their assets and make strategic decisions concerning design, building operation, marketing (rating schemes such as sustainability certification based on LCA), and portfolio management. The 3D-viewer in the platform, rather than the Material Passport, may also help manage a building's resources throughout its lifecycle by locating materials that can be harvested for reuse or recycling at the end of their service life.

The MP, in this case for the demo-project 'Dorpsstraat 1', is a 20-page pdf-file that first describes general information such as building name, address, ownership, intended use, targeted rating schemes etc., as can be seen in *Figure 1* (Madaster Foundation, 2024).

The screenshot displays the Madaster Material Passport for 'Dorpsstraat 1'. It is organized into several sections:

- Material passport Dorpsstraat 1**: Includes the Madaster logo and the title.
- Rating schemes**: Lists 'BREEAM REGISTRATION NUMBER' as 1345 and 'MPG-SCORE' as 0 €/m².year.
- General information**: A central section with three columns:
 - Building**:
 - NAME: Dorpsstraat 1
 - ADDRESS: Marsdijk 1, 4043JW Opheusden, Netherlands
 - DELIVERY DATE: 10/4/1926
 - GROSS SURFACE AREA: 100000 m²
 - GROSS INTERNAL AREA: 215 m²
 - BUILDING PHASE: Renovation
 - USAGE: Offices (Office < 1000m2)
 - Building owner**:
 - NAME: Lanckhorst N.V.
 - Expected lifespan**:
 - BUILDING (YEARS): 50
 - STRUCTURE (YEARS): 50
 - SKIN (YEARS): 50
 - SERVICES (YEARS): 50
 - SPACE PLAN (YEARS): 50
 - STUFF (YEARS): 50
 - EXPECTED LIFESPAN SURROUNDINGS (YEARS): 50

Figure 1 Madaster MP, general building information demo-project "Dorpsstraat 1" (Madaster Foundation, 2024)

The MP then lists the information sources, details the composition of the total mass of all materials in the building by classifying them according to material families, and visualises the distribution of materials according to the “Shearing layers of Change” model by Steward Brand (1994). However, the demo-project had not linked any materials to shearing layers, therefore listing 100% of the materials in category “unknown” (Madaster Foundation, 2024).

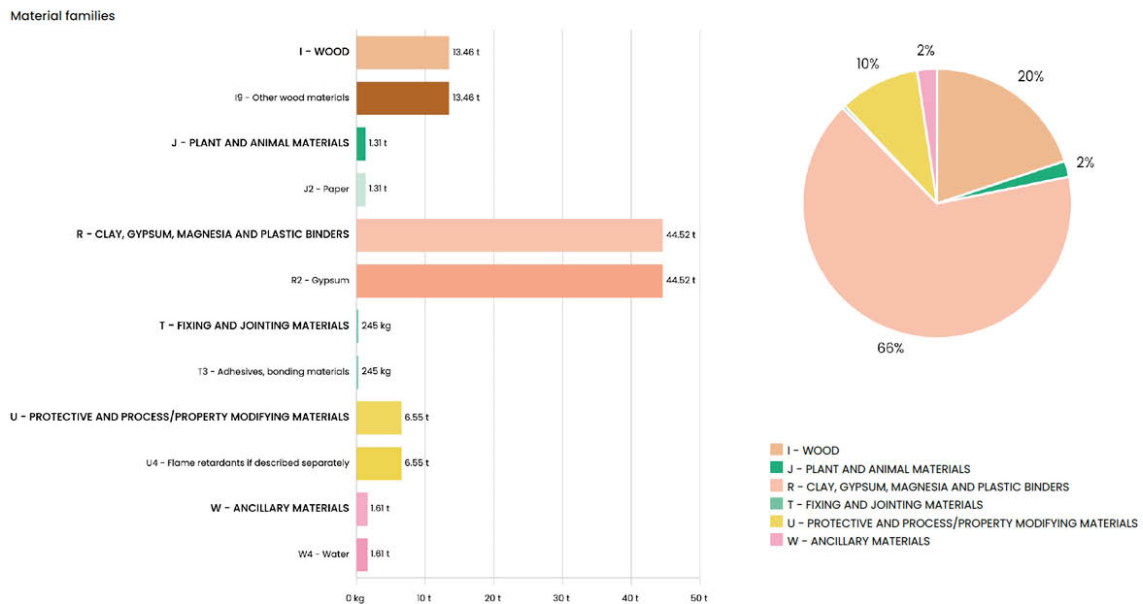


Figure 2 Madaster-MP, material families demo-project “Dorpsstraat 1” (Madaster Foundation, 2024)

The Material Passport then goes on to list the material masses according to material families and shearing layer again, indicating its total weight and percentage of total building mass (Figure 2). Then, the MP presents the buildings score on the “Madaster Circularity Indicator (MCI)”, which is a Madaster-own indicator for what percentage of the building’s materials are already reused materials (secondary materials) and what percentage can be recovered, either for reuse, recycling or downcycling. These percentages are multiplied by one another to give the “CI building score”, which is then multiplied by the percentage of items in the 3D model that have a material attribute to penalise for unknown materials (Figure 3).

MCI Calculation Components

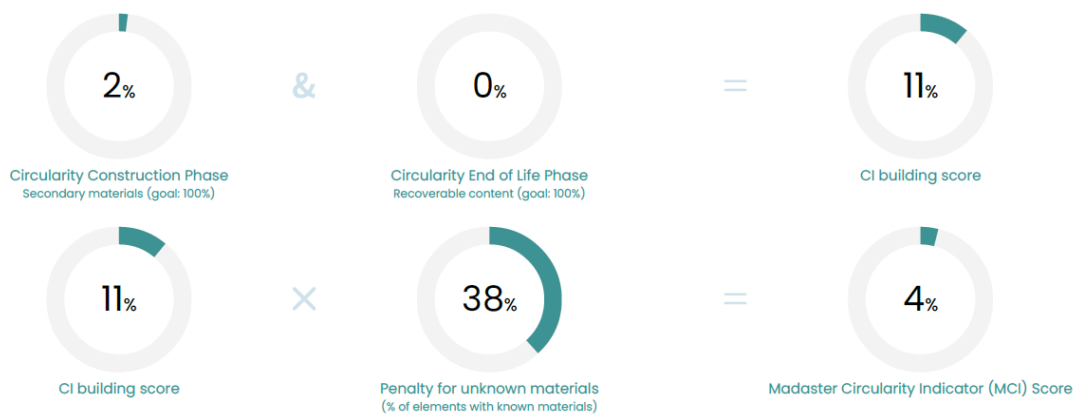


Figure 3 Madaster-MP, Madaster Circularity Indicator (MCI) for demo-project “Dorpsstraat 1” (Madaster Foundation, 2024)

Circularity Construction Phase and Circularity End of Life Phase are then further detailed in “Feedstock Input & Output Flows” before presenting a Lifecycle Assessment (LCA) for the building. The LCA analyses the buildings environmental impact in embodied carbon and is measured in tons of CO₂-equivalent and grams of CO₂-e/sqm throughout the building’s lifecycle phases ‘production of construction products’, ‘construction phase’, ‘building operation’, the buildings ‘end-of-life’, and the ‘materials potential after disassembly’ (Madaster Foundation, 2024). For the demo-project i.e., the highest embodied carbon impact is estimated during the product and disassembly stage as none of the materials are recoverable (Figure 4).

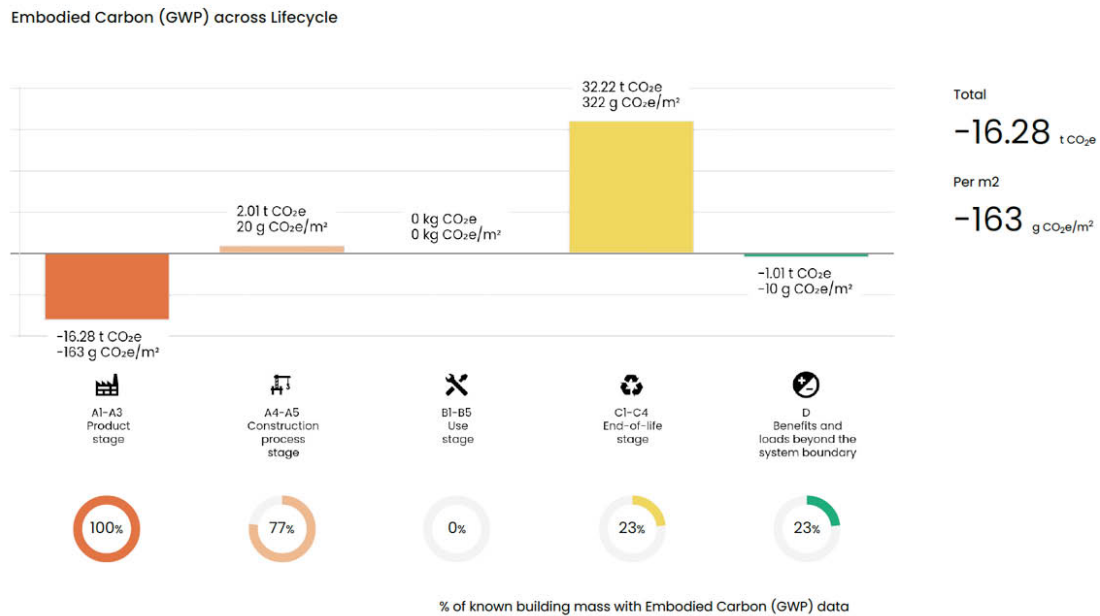


Figure 4 Madaster-MP, embodied carbon per lifecycle phase for demo-project "Dorpsstraat 1" (Madaster Foundation, 2024)

And lastly, the Madaster Material Passport gives an indication of the residual material value, in case of the demo-project: 0€ (Madaster Foundation, 2024).

Appendix E – Barriers Semi-structured Interviews

Table 1 Semi-structured interviews - AEC-general barriers

PESTLE	MP-barriers	Description	Evidence	◇	Σ
Political	Adverse economic-political context (open)	Economy maturity	"So it's also a matter of ... what are people worried about, right? So you need also this mature economy. And let's say the circular economy is a first world problem in my opinion, right?" (RI.3.AP, 2024)	5	5
			"If you try to take any kind of approach that you have for example in the Netherlands and you take it to Greece, it is destined to fail because the maturity of the market is not ... on that level." (RI.3.AP, 2024)		
		National context – information accessibility	"Material passports are great in super developed countries where they measure every single ounce of performance that happens. But in countries that suffer from data starvation ... uh, then that is a much tougher sell to make." (MP.1.PM, 2024)		
		National context – political system	"And then ... you get the example of China where ... they will hang you up upside down if you mention blockchain and bottom up processes, right? Because the party is what is going to determine what is truth and what is not truth." (RI.3.AP, 2024)		
Economical	Chicken & egg problem (open)	Regulation or market incentives?	"How do you create an economy? ... or rather, how do you create a market? ... a lot of times, for example, states create markets or ... conditions create markets, right? So how do you create a market bottom up?" (RI.3.AP, 2024)	5	16
	Industry fragmentation (closed)	Numerous SMEs competing in a highly diversified market without dominant players	"It's a very fragmented industry..." (RI.3.AP, 2024)	2	
	Market-competitiveness (closed)	Slim margins	"We're operating at a margins ... through the whole life cycle of creating an asset, of 1 to 2% profit. I mean ... we are doing a very bad job at what we're doing!" (RI.3.AP, 2024)	9	
		Lack of time	"Everyone is maxed out and working super hard. ... There's not enough time. There's too much work, so why would you do something extra if you don't have to?" (MP.1.PL, 2024)		

		General inefficiency of industry	"Because in most projects, they are so inefficient you are running out of time to actually think of the next level of opportunities..." (RI.3.AP, 2024)		
Social	Change resistance (closed)	Lack of financial incentives	"And passports, or circularity or sustainability, even as such, is in our economy seen or perceived as a cost." (MP.1_D, 2024)	21	21
		Lack of vision	"We are trained from our universities to fulfil a role, right? So you are there to actually do your job. You're not thinking, oh, I have an entrepreneurial kind of aspect that I might go into R&D and actually understand how I can do that better." (RI.3.AP, 2024)		
			"There's not a single client who wants to adopt this from a business or functional perspective." (MP.1.D, 2024)		
		Lack of time	"Lack of structure in the industry to actually look at R&D because R&D is also connected with entrepreneurial aspects, lack of entrepreneurial ambition. And then yeah, time to actually do it!" (RI.3.AP, 2024)		
			"People don't want to change because that means money and time and effort." (RI.1.R, 2024)		
		Technology resistance	"There's also ... the element of individuals that are saying "Oh, I don't know how to use technology!", but ... they use a smartphone everyday and we're not really asking you to do anything much more than what our smartphone can do." (RI.1.R, 2024)		
Fear of the new	"Also the fear of something new... and the laziness of: why? Why should I do that or so ... -barrier?" (MP.1.MD, 2024)				
Technological	Lack of digitalization & digital literacy (closed)	Lack of technology infrastructure	"Technological advancement. This is really where the issues are." (RI.1.R, 2024)	4	4
		Lack of technology literacy & human error in application of technology	"Look at BIM! BIM is like developing in slow motion and there are still architects, I would say more than 50% ... I know students from ETH, from ETH! They start working as an architect and don't work with BIM!" (MP.1.MD, 2024)		
			"Existing systems are fine, but we don't use them in the way that they should be. So then they don't work." (RI.1.R, 2024)		
Legal	-	-	-	0	0
Environmental	-	-	-	0	0
				Total quantity of mentioned barriers: 46	

Table 2 Semi-structured interviews - MP-specific barriers

PESTLE	MP-barriers	Description	Evidence	◇	Σ
Political	-	-	-	0	0
Economical	Lack of financial incentives (closed)	<p>Not sharing data is profitable in the current economic paradigm (asymmetric information – “theory of lemons”)</p> <p>Current MP-inherent value limited to marketing value (enabler), i.e. certification schemes = direct value for stakeholders</p> <p>High upfront costs i.e. for data collection regarding content and format etc. (Material/building survey); as well as high costs for data-validation and -certification (i.e. PwC, SGS etc.)</p>	<p>"People just don't want to have that data out there if they can make money from it." (RI.1.R, 2024)</p> <p>"Lack of information availability, so material passports are great in super developed countries where they measure every single ounce of performance that happens. But in countries that suffer from data starvation ... uh, then that is a much tougher sell to make." (MP.1.PM, 2024)</p> <p>"It comes down to finding ... clear value today for users, ... if there's no regulation forcing you to do anything today, then the only value that you're achieving from doing it is ... you're getting marketing value out of it today." (MP.1.PL)</p> <p>"So the biggest problem is you need to invest to get the right data and the right description." (MP.1.D, 2024)</p> <p>"So if you're a start up, you need to pay 10 thousands of euros to get access to one of those standards, which are basically like the law, that's an issue." (LF.1.LA, 2024)</p>	39	39
Social	-	-	-	0	0
Technological	Inadequate information provision (open)	<p>Lack of information availability & data maturity (data-input: information provision = fundamental requirement for MPs)</p> <p>Reluctance to input data: fear of sharing trade secrets (IP/competitive advantage protectionism/data security/longevity)</p> <p>Human error in data-input</p>	<p>"I think the biggest challenge is that there is an overall lack of data available." (MP.1.D, 2024)</p> <p>"We can't force our users to do as-built models. ... our stance is: it's better to have information that's let's say 85% right than zero information." (MP.1.PL, 2024)</p> <p>"So they ... basically don't want anybody else to be able to make money from their IP. So that means that they will share very limited information..." (RI.1.R, 2024)</p> <p>"I think that people ... are a bit scared of data and security, like how transparent do I have to be? Asset managers or big portfolio management companies, they actually want to have transparency, but just to a certain point." (MP.1.MD, 2024)</p> <p>"Garbage in is still garbage out. You've heard of that, right?" (RI.1.R, 2024)</p> <p>"The problem is that ... there's no validation of these numbers." (MP.1.PL, 2024)</p>	35	95

		Data-input verification (enforcement-barrier)	"The question of trust. Do you trust the centralised entity which is saying that's a correct ... and authenticated certificate...?" (RI.2.R, 2024)		
	Lack of knowledge (open)	Lack of awareness for CE + need for information accessibility	"What we see is that a lot of owners don't care. They do not care at all. ... the owners say: I got the house. Why should I bother about getting the BIM files or getting this MP.1 account?" (MP.1_D, 2024)	15	
		Lack of awareness for value of building and material data (i.e. for project financing & novel business models)	"If a bank... if the residual value of the materials could get included in the financing of a building, then it would really push it forward." (MP.1.PL, 2024)		
			"And I think ... lack of knowledge is a big issue. ... they are not creative enough to see chances for their, for their business or for their, you know, company..." (MP.1.MD, 2024)		
	Technical practicalities (closed)	Digital storage & modelling issues	"The big challenge is data. It's not only for Material Passports, it's everywhere. Like the data is challenging. How do you store?" (RI.2.R, 2024)	25	
			"The first question everybody says: ... can I not just put the Material Passports on a server? ... and the answer is: well, as long as you trust that the entity who maintains the servers is going to be there for the next 50 years, then yes." (RI.3.AP, 2024)		
		Interoperability (complexity) - in between systems/digital technology (BIM, IoT devices etc.)	"Interoperability. This is something that MP.1 also believes in strongly, but we're not there yet. ... there has to be a customer of two different platforms or a customer who wants to move their information from one platform to another" (MP.1.PL, 2024)		
"Part of data entry is just time and effort. So if you can automate that... And that it's not ... a simple thing. You have to have infrastructure like IoT and sensors and things like that integrated." (RI.1.R, 2024)					
Interoperability (complexity) - physical-digital asset connectivity	"Right now, to my knowledge it's not connected ... We need a use case, ... ideally there would be a QR code on every single piece of a building. When that QR code is linked to the material passport ... I get all the facts on it so that I could take this beam and then push it over to the secondary marketplace with a little QR code and then take that digital information and put it on a marketplace so that an architect or whatever on the other side of the country can find it, spec it, and the contractor can buy it..." (MP.1.PL, 2024)				
Technology readiness (closed)	Lack of technology dissemination	"There are secondary marketplaces that exist for buying and selling material products, but they usually exist in isolation." (MP.1.PL, 2024)	20		
		"The challenge I see with ... companies ... buying materials from demolitions and then resell it. It's a super niche thing still right? ... it lacks ... a bit of network effects." (RI.2.R, 2024)			

		Lack of cases as proof of concept, demonstrating viable use cases (ideally on systems level)	"You have to create use cases. You talk about it, but you have to showcase this stuff and ... this is the challenge in the construction industry. They don't believe anything before they don't see it." (MP.1.MD, 2024)		
			"So I think in order to have people really buy into this idea of residual value, we need to get to the point where we've had some buildings that we've calculated the residual value and then we've also gotten to the point where we've disassembled it and we've put those items on the marketplace to be sold. And we can compare like the guess on, uh, like a discounted cash flow model is just a guess versus the reality that we achieved." (MP.1.PL, 2024)		
		Lack of systemic approach	"But we need that to happen at system level so that ... the information today is connected to the information 50 years from now." (MP.1.PL)		
Legal	Regulatory frameworks (closed)	The lack thereof (to support MP-adoption – active/passive)	"If you want to turn the EU into a circular economy, it can only be by force..." (LF.1.LA, 2024)	63	63
			"I think what's slowing down the AEC industry is the lack of regulation..." (MP.1.PL, 2024)		
		Lack of MP-standardization (content)	"One of the challenges going forward: is basically standardizing and deciding what a material passport needs to look like and how it needs to, what information it needs to have." (MP.1.PM, 2024)		
			"I think what's necessary to guarantee this or to enable this, are so-called European harmonised standards, ... they're very technical documents and a lot of times European acts, regulations or directives, they refer to these European harmonised standards, they kind of they become like the law..." (LF.1.LA, 2024)		
		Lack of MP-standardization (data formats)	"The big challenge is data. ... How do you guarantee that it's kind of the right format?" (RI.2.R, 2024)		
			"The law will only say: it has to be interoperable. It has to be machine readable. It has to be easily accessible. And then what that looks like in practise the law doesn't really care about anymore. It just has to work." (LF.1.LA, 2024)		
		Lack of MP-standardization (costs for data-provision/collection)	"To get the data in the correct format, it requires an investment. ... And people are... the market looks at regulators to determine to what level this cost is..." (MP.1.D, 2024)		
"These European standards so far are kept ... behind a paywall, and sometimes they are super expensive, ... So if you're a start up, you need to pay 10 thousands of euros to get access to one of those standards, which are basically like the law, that's an issue." (LF.1.LA, 2024)					
Connected legislation	"If you work with the DPP, then that's not everything of course, because we have other legislation, for example: ... there will be applicable data protection law. ...				

			there might be relevance to the AI act ... all kinds of digital markets legislation as part of the framework as well..." (LF.1.LA, 2024)		
Environmental	-	-	-	0	0
Total quantity of mentioned barriers: 197					

Table 3 Semi-structured interviews - blockchain-specific barriers

PESTLE	MP-barriers	Description	Evidence	◇	Σ
Political	-	-	-	0	0
Economical	-	-	-	0	0
Social	Lack of trust & general scepticism (closed)	Bad reputation	"This is about drugs, guns and illicit activities. ... this is the kind of feeling that most people get about crypto, but we're not talking about that." (RI.3.AP)	24	24
			"I think ... that the users ... don't even trust 100% what we provide them right now. And if you talk about blockchain, you lose the other half." (MP.1.MD, 2024)		
		Fear of misuse/abuse of data (PII/IP)	"There is a big fear that our data is gonna be used against us. ... people are gonna make money from our data when we should be able to make money from it instead of them..." (RI.1.R, 2024)		
			"There are too many stories about crypto people that lost money. This is how the market understand blockchain." (MP.1.MD, 2024)		
Fear of job displacement	"We might ... get to a quick way that does result in job displacement, but ... we'll probably see a rise in new jobs that we're just not even aware of yet." (RI.1.R, 2024)				
Technological	Lack of knowledge (closed)	Don't understand it > aversion/scepticism	"You have to be able to tell it ... what you want it to do, and that's also a problem in terms of lack of knowledge and skills that people have to use it." (RI.1.R, 2024)	16	41
			"One of the problems that exists when we're talking about blockchain is that we're not talking about the actual storage and handling of the data. ... any kind of restrictions ... you will put on the level of the data that is not on the blockchain..." (RI.3.AP, 2024)		
		Don't see necessity	"Why use blockchain for that? Why? That's way too complex. It's way too expensive. Nobody understands it." (MP.1.D, 2024)		
	Technical practicalities (closed)	Interoperability (complexity) - in between systems/data	"You should have essentially secure data containers that maintain that integrity of the data, but also allow for those people who need to read it to actually read it..." (RI.3.AP, 2024)	9	

		protocols (blockchain-Web3 etc.)	"You need a permissionless blockchain and public one to create financial incentives, but then ... any kind of restrictions ... you will put on the level of the data that is not on the blockchain..." (RI.3.AP, 2024)		
		Interoperability (complexity) - blockchain-environment	"One classic problem that exists in blocks in research and blocks in practice actually is that everybody designs a perfect smart contract ... But your problems actually don't lie there. They lie actually on the Oracle problem. So what is actually touching to the blocks and outside the blocks in?" (RI.3.AP, 2024)		
		Ostrom principles	"Blockchains as socio-economic, socio-technical, -economical systems require a set of people to participate. ... We should have at least ... a community of people who are interested in the same problem, trusting the same system..." (RI.3.AP, 2024)		
			"So who is maintaining the system? Who is participating in the system? Who is using the resource but also needs to contribute back?" (RI.3.AP, 2024)		
		Technical feasibility without blockchain	"The entire industry is working with GS1 methodology for unique identifiers. ... getting a unique identifier and that you cannot change it, that's... you don't need blockchain for that." (MP.1.D, 2024)		
	"The first question everybody says: ... can I not just put the Material Passports on a server? ... and the answer is: well, as long as you trust that the entity who maintains the servers is going to be there for the next 50 years, then yes." (RI.3.AP, 2024)				
	Technology readiness (closed)	Lack of technology dissemination & viable use cases demonstrating proof of concept	"People don't trust blockchain yet because it hasn't been around long enough. For there aren't ... viable use cases out there proving to people that actually this is more effective, blockchain's not going to screw you over like a third party is." (RI.1.R, 2024) "We need the killer app and then we need people to start using it to demonstrate it does work, to demonstrate that it's more effective, that it's cheaper, that it ... protects us more as individuals than a third party." (RI.1.R, 2024)	16	
	Lack of systemic approach	"I think you need a cluster of start-ups that would essentially kind of recognise this commoning argument. ... I think we need consortiums in these kind of ideas." (RI.3.AP, 2024)			
Legal	Regulatory frameworks (closed)	Lack of supporting regulation = passive barrier	"We haven't seen ... high enough levels of adoption and blockchain across the board ... I don't really know what they're regulating. So until they know what they're regulating, they can't regulate it." (RI.1.R, 2024) "That's a big question of different paradigms of having a centralised paradigm, ... having regulation in place which are dictating the markets, how it should be, or a bit more liberal approach ... to regulate ... as little as possible and then set up incentive systems..." (RI.2.R, 2024)	9	9

		Legal concepts actively inhibiting blockchain adoption - ownership rights/data protection (EU-definition of PII)	"If you openly share something, you need to make sure it doesn't contain IP of others..." (RI.3.AP, 2024)		
			"There is this one huge, or one big problem of data protection in personal data included in blockchain. ... it's very hard to get rid of personal data in blockchains and personal data in the European Union, and the European Court of Justice just confirmed this recently, is super broad. So a unique identifier could already be a set of personal data." (LF.1.LA, 2024)		
Environmental	Environmental impact (open)	Energy consumption of computing necessary for token mining	"So why come up with something new that's energy consuming?" (MP.1.D, 2024)	1	1
Total quantity of mentioned barriers: 75					

Appendix F – BBMP Opportunities

Table 1 BlockMaterials' current & future BBMP opportunities

Opportunity	Evidence
Facilitating future contracts for material reuse	“Can I facilitate the transfer of ownership of a brick if I deliver the brick in 30, 50, 100 years? BBMPs can provide that.” (01_BM, 2024)
Material Marketplaces	“You have the marketplace the moment it actually physically becomes available, and you have the rights to that moment...” (03_BM, 2024)
Active material stock trade	“The people that own a property can massively grow. So you ... might have someone from Africa owning a piece of real estate here ... and maybe a property is owned by ... 7000 different people one day and the next day, 4000.” (03_BM, 2024)
PaaS (Products-as-a-Service)	“You can basically still keep the ownership with the original producer of supplier and can start the lease or rent ..., which of course creates quite a saving on the upfront cost of construction, which means it becomes more affordable to develop something and which could make housing more affordable.” (03_BM, 2024)
Residual material value transparency	“Because a future price becomes clear, it means that the so-called residual value of the property becomes extremely clear. And so ... purely from a financial perspective, ... it would create an opportunity where there’s actually 10 to 30% of the property value cash collectible...” (03_BM, 2024)
Life Cycle Assessment (LCA)	“Reusematerials mainly focuses on the investigation of buildings and making Material Passports for those buildings which include carbon dioxide calculations. Mainly to look at how much waste is produced with tearing down a building, or mainly keeping as much of the building. So it’s mainly focused on the reuse of the ... products that are in the building. (02_BM, 2024)

Table 2 iov42 current & future BBMP use cases

Opportunity	Evidence
Full asset tracking throughout material life cycle	“You can see what was original data and how the data has changed. ... our platform enables ... full asset tracking, meaning that you actually represent thee quantities of those commodities as they move through the supply chain and represented in form of transactions on the ledger.” (02_iov42, 2024)
Regulatory compliance	“People are having to do a lot more reporting. There are a lot more fines for inaccuracies in their reporting and that’s also where I think they see ... an immutable ledger, a shared ledger becoming quite important.” (01_iov42, 2024)
Premiums for product transparency	“We think that there will be a premium for goods that do have all of the information that you can track in a product passport, so that if people are able to pass those costs on, ultimately to the consumer ... like, how much do we value the ability to know where our product comes from? To know how hazardous it might be, to know how to recycle it... there’ll be cases where there can be premiums charged.” (01_iov42, 2024)

Appendix G – BBMP-barriers Comparative Case-study Analysis

Table 1 BlockMaterials BBMP-adoption barriers

PESTLE	MP-barriers	Description	Evidence	◇	Σ
Political	Adverse economic-political context	Economy maturity	"The obstacle because there is not a market yet. I haven't got enough scale, for example, in demolition companies ..., I haven't got enough refurbishment centres. I haven't got enough upscaling... but that's a question of money. Once the system is running, then you get an upscale in human capital ... It's just lacking money because there were no markets before." (01_BM, 2024)	9	9
		National context - information accessibility	-		
		National context - totalitarian regimes	-		
Economical	Chicken & egg problem	Regulation or market incentives?	"It's called the innovation death. You have to do investments in order to get into the world, but the ecosystem doesn't provide the flow in materials or the flow in money to get your investment running." (01_BM, 2024)	4	25
	Industry fragmentation (AEC-industry)	Numerous SMEs competing in a highly diversified market without dominant players	-	0	
	Lack of financial incentives (BBMPs)	Not sharing data is profitable in the current economic paradigm (asymmetric information - "theory of lemons")	"But non rivalness, that if I consume data, the consumption of you... the data won't diminish. If I eat an apple, then the apple is gone. You can eat an apple but with data that's not the case. If I consume data you can also consume it. So ... and that's a characteristic, nobody will invest because everyone is providing the possibilities for the other to have a free lunch." (01_BM, 2024)	21	
		Current MP-inherent value limited to marketing value (enabler) such as through certification schemes = direct value for stakeholders	"The only real thing people care about is if they can earn money this way. And so I think for a lot of real estate developers et cetera, if you talk purely from saving the planet kind of perspective, it's very difficult to get them to cooperate. If bottom line, it makes a profit for them, then they start really moving." (03_BM, 2024)		

		High upfront costs (MP: data collection, data-validation and -certification; blockchain: DLT implementation)	"On average, it cost maybe €1.50 per square metre to make like a Material Passport of a building and somebody has to pay it..." (03_BM, 2024)		
		Complexity of necessary technology infrastructure	-		
	Market-competitiveness (AEC-industry)	Slim margins	-	0	
		Lack of time	-		
		General inefficiency of industry	-		
Social	Lack of trust & general scepticism (blockchain)	Bad reputation	"You can also include in the transaction all kinds of trust mechanisms like ... like the Uber rating or the Airbnb mechanisms, that is supporting in this ecosystem." (01_BM, 2024)	2	7
		Fear of misuse/abuse of data (PII/IP)	-		
		Fear of job displacement	-		
	Change resistance (AEC-industry)	Lack of financial incentives (i.e. sustainability perceived as cost as opposed to benefit)	-	5	
		Lack of vision	-		
		Lack of time	-		
		Technology resistance	"So that's really a behaviour change that just takes time." (03_BM, 2024)		
		Fear of the new	"And also the people that we work with ... are not up to date ... they do it as they did before because it's easy and it's OK. ... every new detail, every bit of extra information, most of the people say, OK, no, it's too much for me." (02_BM, 2024)		
	Technological	Inadequate information provision (BBMPs)	Lack of information availability & data maturity (data-input: information provision = fundamental requirement for MPs)	"Most buildings ... are pretty old, so the most drawings are also drawn by hand. So we don't have any digital drawings. So yeah, 3D, it's unique to have. So sometimes we ... let a co-contractor do the 3D modelling ... by camera, so you only get the surface, you don't get really the technical detail. ... and on the hand of that we can tag the Material Passport that are generated from CIRDAX ..." (02_BM, 2024)	14
Reluctance to input data: fear of sharing trade secrets (IP/competitive advantage)			"The second one is asymmetric information concerning the quality of materials." (01_BM, 2024)		

		protectionism/data security/longevity)		
		Human error in data-input	-	
		Data-input verification (enforcement-barrier)	"We don't use the Dutch LCA. We use the British ones because they're established by an independent university. In the Netherlands they're provided by the companies themselves and we don't trust these numbers." (01_BM, 2024)	
	Lack of knowledge (CE & MPs/ blockchain)	Lack of awareness for CE + need for information accessibility (MPs)	"It takes a lot of convincing that there's more to a building than just a pile of materials that can be demolished and then be rebuilt on new materials." (02_BM, 2024)	10
		Lack of awareness for value of building and material data (i.e. for project financing & novel business models)	"For example here in the Netherlands, there's ... 2.8 trillion € in real estate and roughly 10 to 30% of that is the material value. So if we can start making that investable directly, and of course, if you reuse a brick in a, another house, you basically save a new brick needing to come out of nature and be produced." (03_BM, 2024)	
		Don't understand blockchain > aversion/scepticism	"It's also the most difficult parts to integrate into the new process because yeah, that knowledge about it, it's pretty slim." (02_BM, 2024)	
		Don't see necessity for blockchain integration with MPs	"The blockchain, the Material Passports. So we tried to connect it, but it's really hard for people to understand." (02_BM, 2024)	
	Lack of digitalization & technology literacy	Lack of technology infrastructure	"Currently we lack the main data infrastructure." (01_BM, 2024)	4
		Lack of technology literacy & human error in application of technology	"You can already be happy if they use a mobile phone, ... so they don't understand that world of doing everything digital first." (03_BM, 2024)	
	Technical practicalities (open)	Digital storage & modelling issues (MPs)	-	8
		Data-entry	"We investigate as much as possible from our desk. And everything that we can find on the drawing that isn't documented, we go to the building site and ... investigate and take photos of every material that we can find. So ... we measure the door in, we say what materials are in it, which frame it's in, what material, which colour, which state it's in, how easy it can be retained from the form it's in?" (02_BM, 2024)	
		Interoperability (complexity) - in between systems/digital technology/decentralized	-	

		data protocols (BIM, IoT devices/blockchain-Web3 etc.)			
		Interoperability (complexity) – physical-digital asset connectivity	"A lot of things start becoming tagged, and so you have this, these asset tagging systems. ... the other way, and that that's more realistic, as we do: we do this, this point cloud renderings of buildings. So this is just like a full digital copy of the building. And then in the digital space, we can just point and click basically and tag it there." (03_BM, 2024)		
		Ostrom principles	-		
		Platform access	-		
		Technical feasibility without blockchain	-		
	Technology readiness (open)	Lack of technology dissemination & viable use cases demonstrating proof of concept	"The same applies for everything that is innovative and is only knowledgeable for a very few people. It's not mainstream, it's only part in the niches of development." (01_BM, 2024)	17	
		Lack of systemic approach	"Now everything is about economies of scale and scope. I have to organise it in a national way by organising big projects." (01_BM, 2024)		
Legal	Regulatory frameworks (open)	Lack of supporting regulation = passive barrier	"A new requirement that will come up, it's probably that you do need to have a detailed report on the CO2 and impact of the property and the circularity. And I think that might still take like five years until that becomes law. But of course then ... you will get like a full rush on this and people will start looking for solutions." (03_BM, 2024)	23	23
		Lack of BBMP-standardization (content)	"First you have to combine all the Material Passports and get all the information kind of equally. So you kind of have ... a handbook of "this is what a Material Passport is", "this is what it needs to register and define"." (02_BM, 2024)		
		Lack of BBMP-standardization (data formats)	"In the Demo-Blog project, we talk about ontologies, how to combine standards with applications like CIRDAX. ...that everyone speaks the same language. In a digital sense." (01_BM, 2024)		
		Lack of BBMP-standardization (costs for data-provision/collection)	-		
		Legal concepts actively inhibiting blockchain adoption - ownership	"Legally, ownership of individual components is not possible because the, the framework is that anything that is attached in a permanent manner to the building is considered part of the building." (03_BM, 2024)		

		rights/data protection (EU-definition of PII)			
		Connected legislation	"So that's another thing, certification of everything. Like, I have to say, OK, a wooden beam can have, I don't know, 15 Newton's hanging on them, ... So you have to kind of recertificate it." (02_BM, 2024)		
Environmental	-	-	-	0	0
Total quantity of mentioned barriers: 117					

Table 2 iov42 BBMP-adoption barriers

PESTLE	MP-barriers	Description	Evidence	◇	Σ
Political	Adverse economic-political context	Economy maturity	"There is a challenge in that as well to make sure these technologies can help entire industries, so it's making sure they're accessible." (01_iov42, 2024)	1	1
		National context - information accessibility	-		
		National context - totalitarian regimes	-		
Economical	Chicken & egg problem	Regulation or market incentives?	-	0	8
	Industry fragmentation (AEC-industry)	Numerous SMEs competing in a highly diversified market without dominant players	-	0	
	Lack of financial incentives (BBMPs)	Not sharing data is profitable in the current economic paradigm (asymmetric information - "theory of lemons")	"There's other information that they ... basically, they monetize and they sell to the customers downstream." (01_iov42, 2024)	8	
		Current MP-inherent value limited to marketing value (enabler) such as through certification schemes = direct value for stakeholders	-		
		High upfront costs (MP: data collection, data-validation)	"The disincentivizing mechanism lies in the fact that some organisations actually don't have a proper digital capture mechanism for all of the data that they provide,		

		and -certification; blockchain: DLT implementation)	so it's on the shoulders of the receivers of data who are liable in front of the government and so on, in front of legislation, to digitalize all of that information." (02_iov42, 2024)		
		Complexity of necessary technology infrastructure	-		
	Market- competitiveness (AEC-industry)	Slim margins	-	0	
		Lack of time	-		
		General inefficiency of industry	-		
Social	Lack of trust & general scepticism (blockchain)	Bad reputation	"It's why we don't talk about blockchain because often if you say, oh, it's blockchain application, people think about, you know, Sam Bankman-Fried or you think of cryptocurrency scams..." (01_iov42, 2024)	3	4
		Fear of misuse/abuse of data (PII/IP)	-		
		Fear of job displacement	-		
	Change resistance (AEC- industry)	Lack of financial incentives (i.e. sustainability perceived as cost as opposed to benefit)	-	1	
		Lack of vision	-		
		Lack of time	-		
		Technology resistance	"If I can just use an e-mail. I'm so used to using emails." (02_iov42, 2024)		
Fear of the new		-			
Technological	Inadequate information provision (BBMPs)	Lack of information availability & data maturity (data-input: information provision = fundamental requirement for MPs)	"There's a spectrum of how data is acquired and how data is verified, so the first is obviously the manual entry, which is what you've been through and that's what a lot of our users ... that's still enough for them. If you think a lot of this data is captured, spreadsheets, shared drives, et cetera, that's what they're used to..." (01_iov42, 2024)	1 5	59
		Reluctance to input data: fear of sharing trade secrets (IP/competitive advantage protectionism/data security/longevity)	"They're sharing a lot of information that they think is commercially sensitive. I think that is where a distributed ledger..., it'll be permissioned... that's where it can become very important." (01_iov42, 2024)		
		Human error in data-input	"But you realise that humans make mistakes on a daily basis. So you always have to have some kind of a mechanism that still allows you to say that, yes, a mistake has been fixed." (02_iov42, 2024)		

		Data-input verification (enforcement-barrier)	"The authenticity and the integrity of tags, whether it's a barcode, QR code, RFID... there's a lot of fraud in the product. ... there's, like, counterfeit and fraud in the product itself. There's also counterfeit and fraud in the tagging itself..." (01_iov42, 2024)		
	Lack of knowledge (CE & MPs/ blockchain)	Lack of awareness for CE + need for information accessibility (MPs)	-	10	
		Lack of awareness for value of building and material data (i.e. for project financing & novel business models)	"I think that might also be a little bit of a misconception that these things are purely a cost and they can't be a revenue centre as well." (01_iov42, 2024)		
		Don't understand blockchain > aversion/scepticism	"Providing everyone with digital identities ... that's a barrier already because you have to provide a solution that would hold their private key so that they can operate on the blockchain ... the providing of a digital identity to people and explaining it to them, ... why ... they have to use something instead of an e-mail..." (02_iov42, 2024)		
		Don't see necessity for blockchain integration with MPs	"One of the barriers is actually the client's understanding of the benefits. So you have to really explain to them what benefits they get..." (01_iov42, 2024)		
	Lack of digitalization & technology literacy	Lack of technology infrastructure	"Some players, the barrier for entry is actually their processes are so centred around paper that it would take immense effort for them to change their processes." (02_iov42, 2024)	8	
		Lack of technology literacy & human error in application of technology	"Even then, when wood goes through a sawmill and a log is being cut down into several pieces, it all relies on a human actually keeping accounting and then linking things together on our platform." (02_iov42, 2024)		
	Technical practicalities (open)	Digital storage & modelling issues (MPs)	-	18	
		Data-entry	"It all relies on humans actually performing their job diligently and tracing all of these things." (02_iov42, 2024)		
		Interoperability (complexity) - in between systems/digital technology/decentralized data protocols (BIM, IoT devices/blockchain-Web3 etc.)	"A lot of the data really exists in different systems. How do you ... eliminate the need for people to have multiple data entry? Because a that's highly unmotivating, but it also leads to questions around what's the source of truth. So that kind of interoperability and integration is also a big barrier." (01_iov42, 2024)		

		Interoperability (complexity) – physical-digital asset connectivity	"You see attempts at barcoding, at RFIDs. That is not going to work in steel seals processed at 900 degrees centigrade, there you can't have a QR code. And also you might have a QR code on the original steel pipe, but then you chop it up, what then what then happens?" (01_iov42, 2024)		
		Ostrom principles	-		
		Platform access	"We have specifically developed a Q-recovery mechanism for the case of loss [of access key] because like it's not as simple as e-mail that you know you would just request a forgotten passport and then the server sends you a recovery." (02_iov42, 2024)		
		Technical feasibility without blockchain	-		
	Technology readiness (open)	Lack of technology dissemination & viable use cases demonstrating proof of concept	"Ultimately you need to have business benefits. So is it going to save people time? Is it going to save them money or earn them more money or is it going to keep them out of jail? And the more case studies or more tangible examples where you can measure the impact of that, in the sceptics own kind of domain ... is really, really helpful there." (01_iov42, 2024)	8	
		Lack of systemic approach	"I think there is a real role for trade associations here for industry bodies to really step up and be very, very practical around these things and look for practical short-term results rather than very long term theoretical approaches to these things ... It's a lot of theory. But not necessarily the knowledge or the skills to be able to test and trial and improve and iterate in that way." (01_iov42, 2024)		
Legal	Regulatory frameworks (open)	Lack of supporting regulation = passive barrier	"The non-necessity to record information hinders the process of full traceability..." (02_iov42, 2024)	10	10
		Lack of BBMP-standardization (content)	"...standardisation, both in terms of what data needs to be captured..." (01_iov42, 2024)		
		Lack of BBMP-standardization (data formats)	"...secondly in what format and how is it shared and own standards around ownership and governance of that data." (01_iov42, 2024)		
		Lack of BBMP-standardization (costs for data-provision/collection)	"...regulation around transparency and traceability. We think that there will be a premium for goods that do have all of the information that you can track in a product passport, so that if people are able to pass those costs on ... to the consumer..." (01_iov42, 2024)		
		Legal concepts actively inhibiting blockchain adoption - ownership rights/data protection (EU-definition of PII)	-		

		Connected legislation	-		
Environmental	Environmental impact (closed)	Energy consumption of computing necessary for token mining	"At the time, ... other solutions that were energy inefficient..." (02_iov42, 2024)	1	1
Total quantity of mentioned barriers: 83					

Eigenaar (organisatie):	
Datum + tijd paspoort generatie:	2023/05/26 15:08:14:200:002
Documentnummer:	23030600000021.001
Aangevraagd door:	Emile Ramaekers

Appendix H

NL/SfB	(21.1)	h2

Materiaal	
Materiaal	
Staal	
Productcode	
00581181	
Categorie	Materiaalgroep
Wanden	Buitenwand, niet constructief
Kleur	Kwaliteit*
Groen	Redelijk
Demontage status*	Producthergebruik
Goed	Product hergebruik
Naam leverancier	
Aantal	
2	
Lengte (mm)	Breedte (mm)
Hoogte (mm)	Diepte (mm)
Volume (m3)	Oppervlakte (m2)
0.29	417.6

Notities en afbeeldingen

Notities

Damwand plaat links

Afbeelding



Locatie materiaal binnen project

Object

Gebouw

Verdieping

Gebouw

Ruimte

00 Constructie

Projectinformatie

Projectcode

230306

Naam project

Beschrijving

Gebouwtype

Meerlaags

Straat

Huisnr.

22

Postcode

Plaats

Projectstatus op moment van paspoortgeneratie

Materialeninventarisatie definitief

Projectfoto



Kadastrale gegevens

Kadastrale aanduiding

Kadastrale oppervlakte (m2)

Kadastrale omtrek (m)

Perceelnummer

Publiekrechtelijke beperking

Appendix I

iov42 Steel Chain – DPP

The following screen shots depict the ‘Steel Chain’ DPP solution developed by iov42 to track steel throughout its life cycle:



Figure 1 Title page summary screen shot (iov42, 2024)

This blockchain-based DPP contains a list of different information related to the product, some accessible for the whole network to read, some with restricted read access for customers who pay a premium (01_iov42, 2024):

- Declaration of Performance, accessible to entire ('private') network
- Environmental Product Declaration, accessible to entire ('private') network
- Recycling Information, accessible to restricted ('private') network – customers paying premium (i.e. recycling company)
- Product Data Sheet, accessible to entire ('private') network
- Quality Inspection Certificate, accessible to entire ('private') network

Existing validations & declaration of performance:

The left screenshot displays a validation checklist titled "Data secured on the iov42 blockchain". The checklist items and their status are:

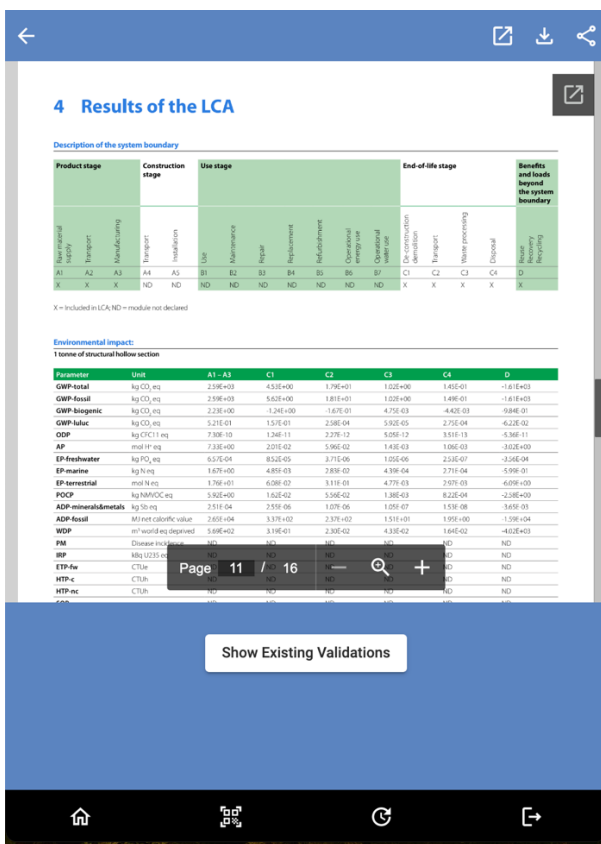
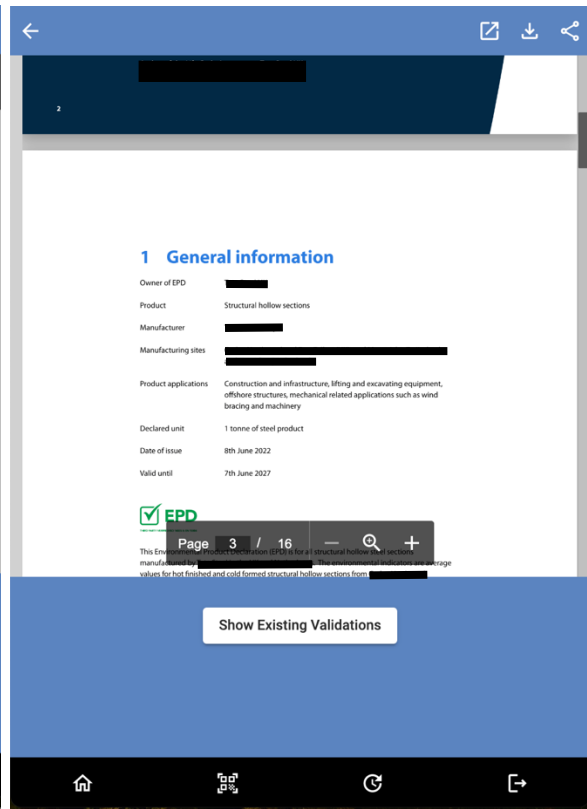
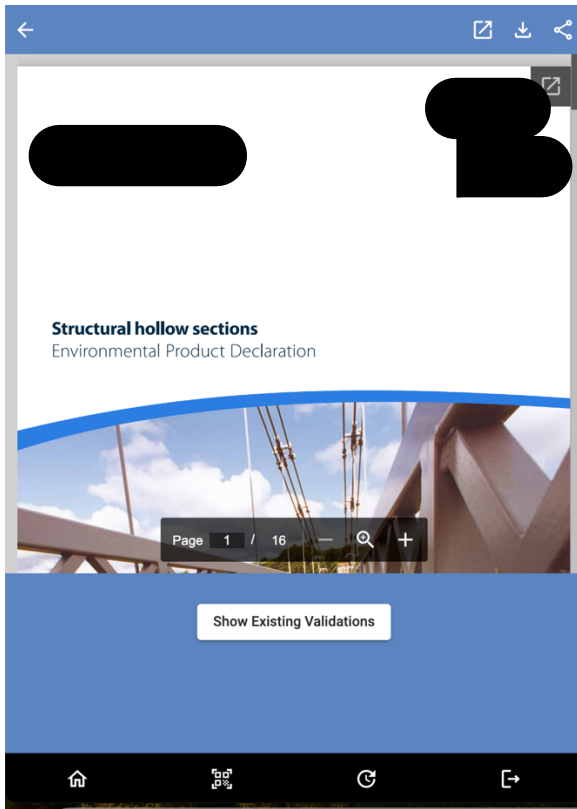
- Certificate Number:
- Date of Issuance:
- Certifier ID:
- Tube Number:
- Product - Label Match:
- Product Passport Identity:
- Product Owner ID:

The right screenshot shows a "Declaration of Performance" document for a "Tetra Biotin" product. The document includes the following information:

- Product Name:** Tetra Biotin
- Manufacturer:** Tetra Systems, Inc.
- System of ANQP:** System of Assessment and Qualification of Certifiers (ANQP) for Environmental Product Declarations (EPDs)
- Product Data Sheet (PDS):** PDS No. 2024-001
- Product Passport Identity (PPI):** PPI No. 2024-001
- Product Owner ID:** POI No. 2024-001
- Product Owner:** Tetra Systems, Inc.
- Product Owner Address:** 1234 Main St, Suite 500, San Francisco, CA 94105, USA
- Product Owner Contact:** +1 (415) 555-1234
- Product Owner Email:** info@tetrasystems.com
- Product Owner Website:** www.tetrasystems.com
- Product Owner Phone:** +1 (415) 555-1234
- Product Owner Email:** info@tetrasystems.com
- Product Owner Website:** www.tetrasystems.com

Parameter	Value	Unit	Method	Standard
Volume	1.0	L	Volume	ISO 2859
Weight	1.0	g	Weight	ISO 2859
Length	1.0	cm	Length	ISO 2859
Width	1.0	cm	Width	ISO 2859
Height	1.0	cm	Height	ISO 2859
Temperature	1.0	°C	Temperature	ISO 2859
Humidity	1.0	%	Humidity	ISO 2859
Pressure	1.0	Pa	Pressure	ISO 2859
Force	1.0	N	Force	ISO 2859
Energy	1.0	J	Energy	ISO 2859
Power	1.0	W	Power	ISO 2859
Current	1.0	A	Current	ISO 2859
Voltage	1.0	V	Voltage	ISO 2859
Frequency	1.0	Hz	Frequency	ISO 2859
Wavelength	1.0	nm	Wavelength	ISO 2859
Speed	1.0	m/s	Speed	ISO 2859
Acceleration	1.0	m/s²	Acceleration	ISO 2859
Angular Velocity	1.0	rad/s	Angular Velocity	ISO 2859
Angular Acceleration	1.0	rad/s²	Angular Acceleration	ISO 2859
Rotational Inertia	1.0	kg·m²	Rotational Inertia	ISO 2859
Stiffness	1.0	N/m	Stiffness	ISO 2859
Damping	1.0	N·s/m	Damping	ISO 2859
Mass	1.0	kg	Mass	ISO 2859
Volume	1.0	m³	Volume	ISO 2859
Area	1.0	m²	Area	ISO 2859
Perimeter	1.0	m	Perimeter	ISO 2859
Surface Area	1.0	m²	Surface Area	ISO 2859
Volume Fraction	1.0	%	Volume Fraction	ISO 2859
Mass Fraction	1.0	%	Mass Fraction	ISO 2859
Molar Fraction	1.0	%	Molar Fraction	ISO 2859
Weight Fraction	1.0	%	Weight Fraction	ISO 2859
Volume Fraction	1.0	%	Volume Fraction	ISO 2859
Mass Fraction	1.0	%	Mass Fraction	ISO 2859
Molar Fraction	1.0	%	Molar Fraction	ISO 2859
Weight Fraction	1.0	%	Weight Fraction	ISO 2859

Environmental Product Declaration (EPD) incl. LCA:



Recycling information:

Mechanical properties			
Yield strength $R_{m, min}$ N/mm ²	Tensile strength R_m N/mm ²	Elongation % min $L_0 = 5,65 \sqrt{S_0}$ specimen	Impact strength 10mm x 10mm
T ≤ 16mm	3mm < T ≤ 100mm	T	°C
355	470-630	22	-20

Chemical composition % by mass									
C	Si	Mn	P	S	Nb	V	Al	Ti	C
max	max	min max	max	max	max	max	total	max	max
0.16	0.50	0.50 min 1.50 max	0.025	0.008	0.050	0.10	0.020	0.03	0.40 0.65

Product data sheet:

Celsius® Weathering Grade
Long life, hot finished hollow sections

Combining the corrosion resistance of weathering steel, with a true hot-finished structural hollow section, Celsius® is now available in weathering grade. Weathering steel forms a dense patina which protects it from oxygen, slowing corrosion for a useful life of 50 to 120 years without galvanizing or painting.

The final shape of Celsius® hollow sections is always formed at normalising temperature, giving an almost complete absence of internal stresses throughout. This gives excellent yield behaviour, coupled with low temperature toughness making Celsius® Weathering Grade ideal for demanding structures.

Certification
Celsius® hollow sections are subject to specific inspection and testing and are supplied with an inspection certificate type 3.1 to EN 10204. All Celsius® sections undergo 100% weld line NDT inspection to EN 10204-2 or EN 10204-3.

Tolerances
Dimensional tolerances are to EN 10210-Part 2 except for corner radius which is max 2T (standard states max 3T).

Recyclability
The physical properties of steel make it the most sustainable choice for a wide range of applications. Steel is strong, durable, versatile, reusable and most importantly, it is 100% recyclable.

Page 1 of 2
Grade 2 hollow sections
in accordance with EN10210-1&2:2006 grade

Source:

iov42. (2024). *Generic Product Data Preview*.

Appendix J

Blockchain technology description

What is it?

Scholars frequently define Blockchain by repeating the same important characteristics. Hunhevicz & Hall (2020) describe a distributed peer-to-peer system for value transactions, that provide an immutable and transparent record of these transactions without a central authority as intermediary. Yaga et al. (2019) also define blockchain as “[...] tamper evident and tamper resistant digital ledgers implemented in a distributed fashion and usually without a central authority.”. By “distributed”, both refer to the decentralized storage of transaction data, meaning without a central repository; and “decentralized” refers to the peer-to-peer consensus mechanism of transactions, which bypasses the authentication process of transactions by central authorities common in traditional value transaction systems such as banks, companies, governmental and authorities. In essence, a blockchain allows the members of a community to record transactions in a shared ledger within that community, making it impossible for a transaction to be altered once it has been published via the standard operations of the blockchain network (Yaga et al., 2019).

J. Li et al. (2019) summarize the key features of blockchain technology. First, blockchain is characterized by its decentralised nature, which means it is made up of a network of multiple “nodes”. Second, immutability is ensured by guaranteeing that transactions cannot be altered after they are recorded in blocks and then added to a chain. Third, J. Li et al. (2019) list reliability as a characteristic of blockchain because each node in the network keeps an identical copy of the ledger. And finally, blockchain ensures security, anonymity, persistence, auditability, resilience, and fault tolerance by using consensus mechanisms and cryptographic operations to authenticate and validate transactions (J. Li et al., 2019). Scholars claim this means that participants of a blockchain network are naturally inclined to trust the network and the truthfulness of the transaction history.

Although a thorough deep dive is beyond the scope of this research, it is imperative that the following sections clarify the basic characteristics that underpin the technology that is being discussed in this study. It will help comprehend the value proposition blockchain makes to Material Passports and the circular transition in AEC. The characteristics include the DLT technology stack, describing the infrastructure and its layers that blockchain technology uses to function; the ledger, meaning the digital record and data structure used by the respective DLT; the peer-to-peer (P2P) network, which enables

decentralized transaction validation; and the governance mechanism used to ensure consensus within the network of nodes. These characteristics lead to the fundamental properties of blockchain, which are central to its value proposition and will be discussed thereafter.

DLT technology stack

Hunhevicz & Hall (2020) present the most comprehensive description of the DLT technology stack, the underlying infrastructure and technological setup, including a distinction of the operations that take place at different layers:

As depicted in *Figure 13*, the Internet Layer represents the foundation. It is the basis for exchanging information across a digital network. The Distributed Ledger Technology (DLT) or Protocol Layer, during this research referred to as blockchain, sits on top of that Internet Layer and is divided into three main elements, the ledger, the peer-to-peer (P2P) network, and its Governance. First, the DLT provides the medium that holds the information that is being exchanged. This medium, called Ledger, records transactions in a secure and verifiable format. Second, the Protocol Layer establishes rules and procedures for the operations of the network, meaning how Ledgers are distributed within the network of peers, as well as the networks consensus mechanisms and crypto economic design. Provided the blockchain can execute code, an extra application layer can be set up on top of it for the implementation of smart contracts that automate and enforce contractual agreements (Hunhevicz & Hall, 2020).

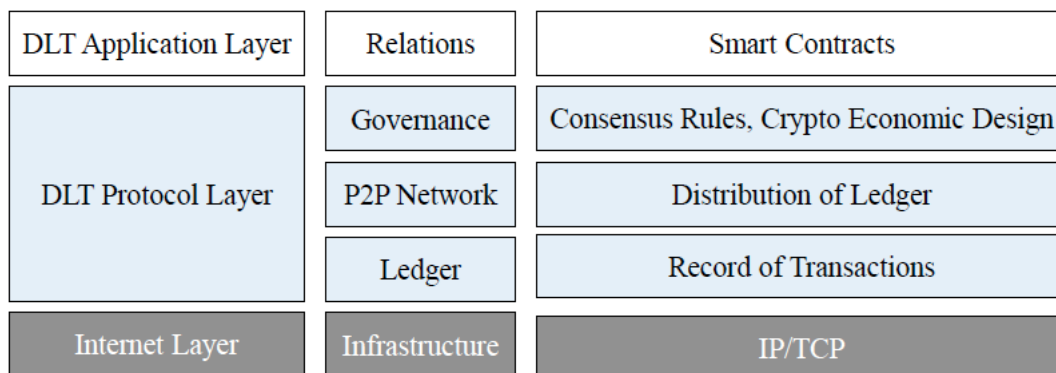


Figure 1 DLT technology stack as described by Hunhevicz & Hall (2020)

Ledger

The central data structure of a DLT Protocol Layer is the so-called ledger, a record of every transaction made. Ledgers can be setup in multiple ways, however the most well-known type of ledger is “blockchain” as presented first by Nakamoto (2008). The blockchain ledger links blocks of transactions in a continuous sequence while guaranteeing data integrity by encrypting them with hashes – a hash is a mathematical code that binds each

block to its predecessor irreversibly; as a quasi-fingerprint of the data, it immediately makes any manipulation visible (Hunhevicz & Hall, 2020).

Re-recording the entire ledger every time a new transaction is made necessitates a lot of computing power and high levels of energy consumption (J. Li et al., 2019). Therefore, other ledger types have emerged that provide other characteristics. However, a Protocol Layer is generally limited to one Ledger at a time. An example for another ledger is the Directed Acyclic Graph (DAG) which allows parallel transaction confirmations and thus provides improved scalability (Hunhevicz & Hall, 2020).

P2P network

The second central element of the DLT Protocol Layer is the peer-to-peer (P2P) network, essential for enabling decentralization and crucial for the operation of the technology. As the name Distributed Ledger Technology (DLT) already indicates, ledgers are spread across many nodes, making it possible for a community to record transactions in a shared fashion (Yaga et al., 2019). In a P2P network, every transaction is broadcast to every node in the network, who each validate the transaction's legitimacy by analysing its structure and past activity using agreed-upon algorithms (Yaga et al., 2019).

P2P networks are differentiated in two ways. First, nodes can have differing read- and write-permissions. Either anyone can set up a node and by participating in the consensus mechanism write transactions to the ledger (Hunhevicz & Hall, 2020). This is called a permissionless ledger and it promotes more decentralized network structures. Or setup- and write-permissions are unequally distributed among the nodes. In that case the ledger is called a permissioned ledger. The second P2P distinction has less to do with the editing rights of participants but rather access rights of non-participants and describes whether a ledger is public or private (Hunhevicz & Hall, 2020). Public ledgers allow anybody to view their structure and content. Conversely, in a private ledger, only a restricted number of members is allowed access. Unsurprisingly, public ledgers tend to make use of a structure of permissionless, and private ledgers of permissioned nodes (Hunhevicz & Hall, 2020). Nevertheless, combinations vice versa exist, as can be seen in *Figure 14*.

Governance

The governance of a DLT Protocol Layer is critical because it establishes the rules for how participants interact with the system. Two elements are important for governance and essential to the operation of the Protocol Layer: the consensus mechanism that defines the way entries to the ledger are recorded, verified, and validated (Hunhevicz & Hall, 2020), as well as its Crypto-Economic Design (CED).

The most well-known consensus mechanism is called "proof-of-work" and was proposed by Nakamoto (2008) along with the introduction of Bitcoin. Participants compete to solve a mathematical function imbedded in a new block of verified transactions, and whomever does so first gets to add the block to the blockchain.

Subsequently, that participant, or node, is rewarded with a native token such as a Bitcoin (J. Li et al., 2019). This process is called “mining” due to its significant required computing effort. After mining the block, the node publishes the new chain and all other nodes in the network verify and record a copy of it. According to J. Li et al. (2019) transactions are usually verified if a consensus is reached by a simple majority. This design is aimed at enhancing the robustness and resilience of the system by distributing the data replication over all participating nodes. Data integrity is guaranteed due to the complexity and effort needed to modify already hashed transactions: if an attacker wanted to tamper a past block, they would need to redo the proof-of-work of the block they intend to manipulate as well as all blocks after it, and then catch up with and surpass the work of all honest nodes. This is highly unlikely but requires honest nodes to retain control over the majority of the computing power to preserve data security (Nakamoto, 2008). Following this description, it’s obvious that proof-of-work requires a lot of resources. Therefore, other methods have emerged that require less CPU effort. Proof-of-stake is an example of a consensus mechanism, in which nodes invest a monetary stake when confirming transactions, aiming at making the ledger safer.

On top of consensus mechanisms, there is a second ingredient to governance, as hinted earlier. Consensus mechanisms in public DLT systems are backed by a Crypto-Economic Design (CED), an incentive structure that ensures system security by combining the encryption of transactions and chaining of blocks with hash functions and providing monetary rewards for “miners” to encourage behaviour in the interest of the network (Hunhevicz & Hall, 2020).

Private DLTs, on the other hand, usually don’t need a CED, because the consensus in a private ledger depends more on permissions awarded to nodes and is therefore independent of financial incentives. Moreover, transaction fees might not be required because interactions can be limited to a small number of well-known participants (Hunhevicz & Hall, 2020).

Smart contracts

As mentioned earlier, ledgers also enable the creation of an application layer on top of their own infrastructure, if they support “Turing-complete language” (Hunhevicz & Hall, 2020). With that, Hunhevicz & Hall (2020) refer to the most widely used programming languages such as Python and JavaScript, which, given enough time and memory, have the potential to solve any computational problem. The application layer enables self-executing code protocols, known as “smart contracts”. In fact not contracts in the conventional legal sense, “smart contracts” could be programmed in such a way, that they perform different contractual tasks based on the ledger's state and thus imitate contractual duties in a functional way (J. Li et al., 2019). These contracts provide security and dependability since they run on a ledger with a certain governance mechanism and this way essentially remove the need for intermediaries and central authorities. J. Li et al.

(2019) describe smart contracts as the most important aspect of blockchain technology, because they bear the potential to handle and automate a variety of tasks, such as managing digital assets called tokens (currencies, securities, utilities etc.) and establishing autonomous processes (Hunhevicz & Hall, 2020). However, the authors also emphasize need of carefully coded smart contracts since they run on an encrypted Protocol layer, meaning their code is also unchangeable unless programmed to be updateable (J. Li et al., 2019).

Fundamental properties

The technology stack and its components described above lead to a couple of fundamental properties that are inherent to blockchain technology. Scholars frequently argue it is these properties that instil trust among participants and in the system and make it possible to avoid a trusted third party (Hunhevicz & Hall, 2020; Hunhevicz et al., 2022; Li et al., 2019). As these fundamental properties are the characteristics at heart of the discussion whether blockchain can add value to AEC practice and potentially solve current MP-deficiencies, it is important to discuss them in the following section.

As depicted in Figure 14, the fundamental properties are immutability, non-repudiation, integrity, transparency, and equal rights (Hunhevicz & Hall, 2020). Immutability guarantees that once a transaction is validated via the agreed-upon consensus mechanism and added to the chain of blocks, they cannot be modified anymore. Non-repudiation makes sure that each transaction is recorded just once in the ledger. Data integrity is maintained by verifying the completeness and authenticity of the data recorded on the ledger using cryptographic tools. Transparency is the natural result of granting public access to the ledger, although the degree of transparency varies depending on whether the blockchain is private or public. Similarly, equal rights in a blockchain refer to the equally distributed ability of nodes to read and write to the ledger. And again, equal rights in a blockchain depend on whether it uses permissionless or permissioned nodes (Hunhevicz & Hall, 2020).

The previously mentioned design options of permissioned or permissionless nodes as well as public or private ledgers has an impact on the fundamental properties of that DLT Protocol Layer as described by (Hunhevicz & Hall, 2020) and depicted in Figure 14. The design options are: private permissioned, private permissionless, public permissioned, and public permissionless.

Design Option	Comment	Examples	Fundamental Properties					Overall	Performance
			Immutability	Non-repudation	Integrity	Transparency	Equal Rights		
Centralized	Central databases with a single or alternative providers	-	n	n	n	n	n	↓	↑
Private Permissioned DLT	DLT with permissions on both read & write-access	Hyperledger Fabric ¹ , Corda ²	(y)	(y)	y	n	n		
Private Permissionless DLT	DLT with permissioned read-access & permissionless write-access	Holochain ²	y	y	y	n	y		
Public Permissioned DLT	DLT with permissionless read-access & permissions for write-access	EOS ¹	y	y	y	y	n		
Public Permissionless DLT	DLT with permissionless read access & permissionless write-access	Bitcoin ¹ , Ethereum ¹	y	y	y	y	y		

Figure 2 Interrelations of different design options of DLTs and fundamental properties (Hunhevicz & Hall, 2020)

Different DLT design options affect the weighting of and emphasis on different fundamental properties (Figure 14). In general, it can be said that the overall constellation and total amount of fulfilled fundamental properties declines from private permissioned to public permissionless DLTs, but that the overall performance (efficiency) of the system increases vice versa as the number of nodes declines. A configuration with more permissions (restrictions) needs to compensate a lack of technological trust with trust in its users or third-party intermediaries (Hunhevicz & Hall, 2020). Only data integrity remains unchanged across the design options as the cryptographic hash functions apply to all variations.

Understanding which fundamental properties are necessary for a specific use case is critical for choosing the right DLT architecture. On one extreme, a public permissionless blockchain structure maintains the maximum degree of technology-based trust by providing all fundamental properties. Public permissioned DLTs restrict write access and thus sacrifice equal rights. In contrast, private permissionless systems restrict read access of nodes while allowing them to publish without constraint. This could be useful if one wanted to establish immutability and non-repudiation in private ledgers and communities of interest. And lastly, private permissioned DLTs restrict both read- and write-access for participants, jeopardising transparency, and equal rights. At the same time, external parties cannot verify whether a ledger has been updated by a conspiring majority and thus also affects immutability and non-repudiation. Certainly, this reduces the level of trust in the technology, but it may not significantly affect network participants if they trust their network's governance structure (Hunhevicz & Hall, 2020).

Summary & definition

Blockchain technology is a decentralized system for facilitating value transactions various kinds within a peer-to-peer network that avoids a trusted third party as controlling

authority. Transferred values can include data sets, records of ownership, proof of certifications, records for supply chain tracking and many more.

Blockchain is set up in a three-layer technology stack: based on the Internet Layer is the Protocol Layer, consisting of an immutable ledger, which is distributed among nodes in a peer-to-peer network and regulated by consensus mechanisms such as proof-of-work or proof-of-stake. These layers work together to produce the fundamental properties of blockchain: immutability, non-repudiation, integrity, transparency, and equal rights for all participants. So long as the ledger can process code, an application layer can be set up for the execution of smart contracts.

Potential for AEC?

The following chapter will discuss the potential blockchain technology holds for the AEC sector. This has been covered in literature, notably by Hunhevicz & Hall (2020), J. Li et al. (2019), and Q. Li & Wang (2021). The following chapter will therefore outline blockchain's potential for AEC before describing some potential use cases and discuss the question whether a blockchain is even necessary in construction.

Blockchain for construction

The value proposition of distributed ledger technology (DLT) for the AEC sector has recently been discussed extensively in literature. As Hunhevicz & Hall (2020) stress, the AEC sector is characterized by a decentralized landscape and work is almost entirely project based. At the same time, it often sees long-term collaboration among many stakeholders with various interests. This organizational complexity is by nature accompanied by issues such as a lack of trust in between project partners, poor information and knowledge sharing, and dispersed supply chains (Hunhevicz & Hall, 2020). These issues frequently cause delays and cost overruns, as well as legal disputes and sometimes even project failure (J. Li et al., 2019). McKinsey Global Institute (2017) even estimate a productivity gap in the construction sector of a staggering \$1.6 trillion in annual losses for which J. Li et al. (2019) name digitalization as a whole as the most promising solution. It's obvious the construction industry is in pressing need for a framework that can build trust among stakeholders, promote communication, and integrate the building life cycle stages from design to construction, operation, and decommissioning. Blockchain emerged as a concept to allow online payments without the need of an intermediary (Nakamoto, 2008) and has since long expanded into fields such as the energy market, E-Government applications, or supply chain and carbon emission traceability across various industries (Babel et al., 2022; Rioux & Ward, 2022; Sedlmeir et al., 2021; Wang & Su, 2020). As a result, it seems appropriate to raise the question whether blockchain technology also bears the potential to mitigate some of the issues encountered in construction.

In fact, scholars believe the industry's needs are well aligned with blockchains value proposition (Hunhevicz & Hall, 2020; Q. Li & Wang, 2021). Its fundamental properties propose a special cure for the sector's trust and coordination struggles. Stakeholders in construction projects could i.ex. profit from transparency and immutability, expressed in the independently verified real time tracking of transactions and project progress, and that way reduce the amount of disagreements (Hunhevicz & Hall, 2020). Additionally, smart contracts present themselves as a powerful tool to introduce higher efficiency and accuracy in the optimization and automation of business operations (Hunhevicz & Hall, 2020). They offer the possibility to self-execute specific contract terms upon pre-set parameters (J. Li et al., 2019). In practice that could i.ex. mean that project progress could be tracked on a ledger and smart contracts could automatically issue payments from clients to contractors when the successful installation of an element is recorded. And so it seems as though blockchain's fundamental properties and inherent characteristics have the power to combat some of the sectors most pressing issues by simplifying complex supply chain and project management, streamline payments, and automate processes, and thus promise sector-wide improved accountability and efficiency.

Use cases

In order to provide a better understanding of blockchain's potential for the AEC sector, the following section will give an overview over the most important possible areas of implementation of DLT in construction, as summarized by Hunhevicz & Hall (2020). Although J. Li et al. (2019) also present seven major areas for DLT-application in the building sector, divided in use-categories such as the Smart Energy, Smart Cities and the Sharing Economy etc., the cases presented by Hunhevicz & Hall (2020) most poignantly visualize blockchains potential. These use cases build on the main value propositions of DLT in construction: immutability, non-repudiation, integrity, transparency, equal rights, and trust. The authors identified and clustered the most important blockchain applications and assigned the possible DLT design options for the particular use case (*Figure 15*), including their need of a Trusted Third Party (TTP).

		No DLT	DLT (TTP possible)			DLT (TTP not possible)				
		(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)
1	Internal Use for Administrative Processes									
1.1	Notarization and Synchronization of Documents	X	X	X						
2	Transaction Automation between Stakeholders with Smart Contracts									
2.1	Triggering Payments	X	X	X	X					
2.2	Triggering Contract Deliverables	X	X	X	X					
2.3	Self-executing Contract Administration	X	X	X	X					
2.4	Automated Data/Information Sharing	X	X	X						
2.5	Automated Code Compliance Checking	X	X	X	X					
3	Immutable Record of Transactions									
3.1	Timestamping of "Value" Transactions	X	X	X	X					
3.2	Record of Changes in digital models (BIM)	X	X	X	X					
3.3	Tracking of Supply Chain Logistics	X	X	X	X					
3.4	Tracking of Project Progress and Worked Hours	X	X	X	X					
3.5	Record of Maintenance and Operations Data	X	X	X	X					
3.6	Tracking of Health & Safety Incidents	X	X	X	X					
3.7	Verification of Installation Tasks	X	X	X	X					
3.8	Record/Notarization for Regulation and Compliance	X	X	X	X					
4	Immutable Record of Assets/Ownership									
4.1	Record of Ownership in BIM (IP-Rights)	X	X	X	X					
4.2	Record of Ownership for Physical Assets (e.g. Property)	X			X					
4.3	Managing Identities for Reputation (People, Contractors)	X			X					
4.4	Material & Product Passports (Provenance and Properties)	X			X					
5	Coins/Tokens as Payment or Incentive Scheme									
5.1	Payment in Cryptocurrencies								X	
5.2	Shared Accounts & Insurances	X	X	X	X					
5.3	Incentives over the Whole Building-Lifecycle					X	X	X	X	X
6	Decentralized Applications (DApps)									
6.1	Decentralized Market Places for Products and Services							X	X	
6.2	Decentralized Common Data Environments (CDE) for Digital Models					X	X	X	X	X
7	Decentralized Autonomous Organizations (DAOs)									
7.1	Automated Building Maintenance Systems					X	X	X	X	X

Figure 3 Blockchain-for-AEC-use cases with possible DLT design options (Hunhevicz & Hall, 2020)

The first use case identified by Hunhevicz & Hall (2020) is blockchain as a tool to improve internal administrative processes, especially when it comes to managing complicated projects with several parties. If a project-organisation wanted to set up a transparent, and unchangeable record of project alterations and a reliable history of stakeholder's activities and project progress, blockchain could be employed for the storage and notarization of administrative tasks. It would help streamline processes and lower the possibility of disagreements or mistakes, making administrative work easier while guaranteeing that all parties involved have access to the most recent and consistent data. This is specifically promising for the management of complex building projects.

As already indicated earlier, smart contracts have the potential to introduce transaction automation to construction practice. Coded to automatically perform operations based on the fulfilment of predefined criteria, smart contracts can execute payments automatically when a specific project milestone i.e.x. is completed and recorded on the ledger. This extends past the construction phase to building operation, where project contributors could be rewarded automatically for compliance with specific building performance goals (Hunhevicz & Hall, 2020).

Third, blockchain's probably most significant impact on industry practices is the immutability of the record of transactions, as it is the basis for many operational purposes and use cases like transaction automation. Blockchain timestamps value

transactions. That way, it assures that changes to i.ex. BIM models are documented in a verifiable and immutable way. It's also fundamental to track and record supply chain logistics, verify installation tasks, track project progress, record maintenance and building operation data etc. automatically (Hunhevicz & Hall, 2020).

Like immutable records of transactions, Hunhevicz & Hall (2020) also identify blockchain's potential to keep immutable records of assets and identities. As a fundamental component for asset management in a circular economy for example, blockchain can create a unique digital representation of a physical asset to make the accurate record-keeping of ownership possible. Naturally, this proposes the integration with Material Passports to introduce accuracy and reliability to the recording of product and material information of components in a particular building. Blockchain-based Material Passports (BBMPs) could help ensure quality, simplify certification application, and most importantly permit material reuse by providing a reliable, unchangeable record of a products lifespan. Subsequently, this application of blockchain in the construction industry not only improves accountability and efficiency, but also encourages sustainability and circularity (Hunhevicz & Hall, 2020).

Next, with tokens and cryptocurrencies, blockchain technology also introduces financial incentive schemes to the building industry. Tokens can be used to create shared risk and reward structures in addition to their sole function as payments. Together with smart contracts, Hunhevicz & Hall (2020) argue financial incentive schemes using tokens may encourage stakeholders to prioritize long-term quality and sustainability over short-term profits.

So-called DApps (Decentralized Applications), are blockchain-based applications, governed by smart contracts instead of a TTP (Trusted Third Party). DApps enable decentralized marketplaces for products and services i.ex., leveraging the fundamental properties transparency and equal rights for fair tendering procedures. Project collaboration might equally profit from DApps as digital models could be safely stored in decentralized CDEs (Common Data Environments combining blockchain with cloud storage), reducing dependency on external services and improving data security (Hunhevicz & Hall, 2020).

And lastly, blockchain technology can enable so-called Decentralized Autonomous Organizations (DAOs) in the construction sector, which make use of the fundamental properties of DLT and smart contracts to function completely independent of human intervention. Integrating multiple innovations like IoT sensors and BIM for building operation monitoring, DAOs could execute asset management operations such as the ordering of spare parts in an automated way (Hunhevicz & Hall, 2020).

However, as indicated in *Figure 15*, except for DApps and DAOs most use cases do not exclusively demand the implementation of blockchain technology; while possibly

enhanced by blockchain, they can also be realized without it. Therefore, it is worth questioning whether blockchain is truly necessary in AEC. Accordingly, the following section will present a useful framework developed by Hunhevicz & Hall (2020) for the decision whether to employ blockchain in a certain use case and if so, what design option to choose.

Do you need blockchain in construction?

Even though academia has explored various possible use cases for the integration of DLT in construction industry practice and is, for the most part, optimistic about its potential, the question remains whether AEC really needs blockchain. There seems to be no straight forward answer to this question. Much less, use cases depend on so many variables that they differ greatly. Therefore, Hunhevicz & Hall (2020) developed a simple three-step decision framework that will help practitioners in assessing the need of DLT on a case-by-case basis (Figure 16).

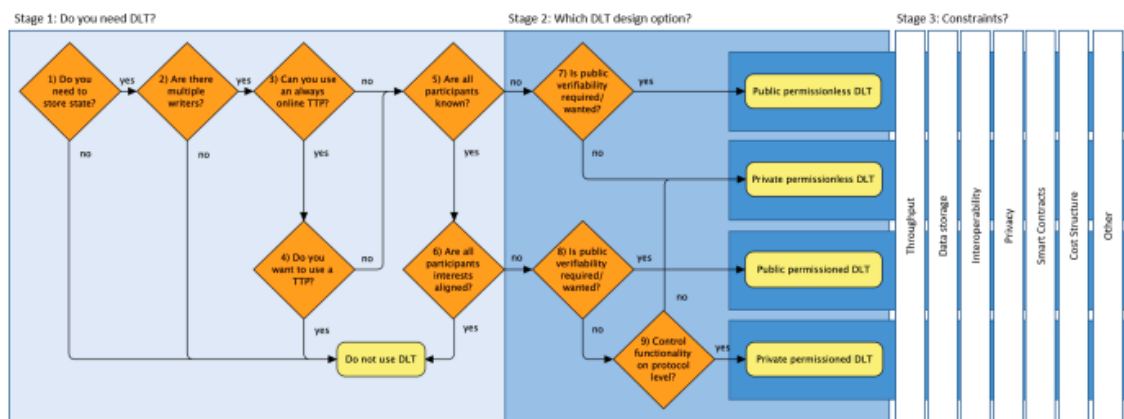


Fig. 2. Combined framework sourcing from eight decision frameworks (see Table 5) to decide for a DTL design option in three stages based on their fundamental properties (TTP – trusted third party).

Figure 4 Decision making framework for assessing blockchain systems architecture necessity (Hunhevicz et al., 2022)

The framework is divided into three stages: whether or not to use a blockchain architecture in the first place (light blue), then, if a DLT is necessary, what design option to choose (azure), and third, evaluate the possible technical constraints that could influence the choice (white boxes).

Wessling et al. (2018) and Hall et al. (2018) suggest understanding the involved actors and their interactions is essential to design the network architecture. Therefore, the aim of stage one is to critically reflect if the use cases call for the application of a blockchain architecture, asking a series of questions which, if negated, lead to blockchain being disregarded. The first question asks whether a “state” needs to be stored. This could be anything from a timestamped record of a financial transaction, a proof of ownership or property right, to the location of a physical asset along a supply chain. The framework

then assesses whether the data requirements are more than what standard databases can handle in terms of immutability and access, i.e. how many parties need write-access and whether it makes sense to use a TTP. Blockchain is then proposed if eliminating intermediaries is important despite possible performance trade-offs.

If the decision is made for a blockchain system setup, the framework guides the decision making towards the specific kind of DLT design in stage two. By evaluating whether participants need to be known and whether their interests are aligned, a decision is made for a permissioned or permissionless system of nodes. The selection of a public or private ledger is then made in a next step, based on the assessment of privacy requirements.

In stage three, the framework tackles technological restrictions and needs that may have an impact on the chosen design option. Transaction performance, data storage requirements, the interoperability of systems, privacy requirements, system setup and maintenance costs, as well as the option for smart contracts play a crucial role in the evaluation. And lastly, possible additional concerns Hunhevicz & Hall (2020) mention are how complex it is to integrate the new technology with current systems, regulatory constraints, as well as the potential to scale. All these factors could potentially change the initial choice of a blockchain design option if a specific characteristic or constraint is prioritized.

For stakeholders in the construction sector, this framework offers a good foundation for assessing whether to use blockchain technology for a particular use case. The step-by-step guidance can help building industry experts align their approach to blockchain implementation strategically with project specificities and overall corporate goals.

Blockchain-potential for AEC (conclusion)

The question whether the construction industry needs blockchain technology seems to be the wrongly formulated. No one categorically denies its potential. Instead, the question should rather be “In what case does AEC need blockchain?”. Hunhevicz & Hall (2020) and Q. Li & Wang, (2021) i.e. believe in blockchain’s value proposition and its potential to help the AEC industry meet various needs such as improvements in efficiency, collaboration, and sustainability. At the same time, scholars highlight new obstacles presented by blockchain, such as legal, technological, and collaboration concerns that need to be handled (J. Li et al., 2019).

The choice for or against blockchain technology should be made on a use case basis, considering the particular demands of each case. Based on the decision framework presented by Hunhevicz & Hall (2020) the need for a blockchain infrastructure in AEC comes down to several factors such as the complexity of multi-stakeholder collaboration and their respective relationships, the need for transparency and trust in collaboration and whether one wants an intermediary to establish these, the need for record-keeping and compliance, and an increasing need for automation.

Appendix K

Reflection

The following reflection is subdivided into four chapters: product, process, planning, and personal note.

Product

The culmination of my work integrates project documentation from case studies, stakeholder interviews, and a literature review. Through this process, I gained significant insights not only into all aspects of the novel technology blockchain-based Material Passports (BBMPs) with its underlying concepts and its value proposition for the circular transition of the construction sector, but also into the complex ecosystem surrounding its integration into AEC practice. However, I identified areas for improvement, such as incorporating more participants in semi-structured interviews, incorporating more case studies and corresponding interviews to substantiate findings, as well as potentially enrich the findings with validation round of focus group discussions, presenting the findings from prior methods. Further, a more comprehensive analysis of potential use cases for BBMPs could be developed, as well as recommendations for what barriers to prioritize in future action. Despite these limitations, my research approach and focus on the research question proved effective.

My observations were shaped by diverse perspectives from various stakeholders. The explorative nature of the semi-structured interviews with experts from academia and practice shaped the final outcomes beyond my initial expectations. The findings from this research hold value for future research and advancements in the understanding of BBMP-adoption for a circular transition. My research methodology is adaptable and considers the contextual nuances of its application.

Relation research with MBE

With its emphasis on sustainable development and stakeholder-centered management of buildings and urban environments, the master's program "Management in the Built Environment" offers a theoretical framework for investigating innovative solutions in the AEC industry. In line with this, the studio "Sustainability transitions and the transformation of port cities," has a particular emphasis on the development of sustainable transformative practices. With the goal of accelerating the transition to a circular built environment, this graduation project enhances these topics by looking at real-world applications and analysing the factors that hinder their adoption, particularly examining a technology that provides significant potential to enable circular practices in the Architecture, Engineering, and Construction (AEC) sector.

Process

Throughout my thesis process, I didn't meet with faculty tutors and my graduation mentors as regularly as I would have liked or needed. Nevertheless, the faculty tutors contributed to shaping my final research design and methods, particularly in refining the research scope, helping select

the right methods and maintaining an exploratory focus. Further, being the very few experts in the field, they provided considerable support in understanding the underlying concepts of BBMPs.

My main mentor was extremely integrating, welcoming me to the broad network of his research group “IC group”, which entailed presentations on a regular basis, workshops, and the invaluable opportunity for me to reach out to relevant researchers in the scope of my research.

I believe my research methods supported my research. Furthermore, I integrated feedback from my mentors, particularly following P1 and P2. However, fewer meetings during P1 and P3 resulted in less feedback, and the extensive time I took to execute my literature review limited the discussions to early parts of the thesis, as well as conceptual aspects rather than content and methods for data analysis.

In retrospect, I would have needed more feedback sessions immediately following P2, pushing the development of my work. However, this impacted by multiple absences as well as my own lack of sense for urgency.

Planning

Following P2, P3 arrived fast, where I had aimed to showcase initial findings. However, at that stage, I had conducted several interviews and analysed nothing. Simultaneously, my work was significantly halted by a very detailed revision of my literature review, as I realized there was still significant foundations to my research to understand. Therefore, the transition to analysis was incomplete at P3.

From P3 onward, substantial progress was made despite persistent time constraints, and tangible results began to emerge. An important lesson learned was the significance of efficiently planning the coding of interviews to gain valuable insights quickly. Further, effective time planning was a necessary learning to solve the time constraints.

Personal note

Starting this research project, I was highly enthusiastic to learn about novel technologies that I knew nothing about, as well as their potential to enable circular practices. I had a gut feeling that technologies such as Material Passports, T&T, blockchain technology, but also novel business models such as PaaS and operational lease would become relevant for my future practice as an AEC professional, making me seek understanding. Ironically, throughout exploring the domain of blockchain-based Material Passports (BBMPs) and all related technologies and concepts, I gained incredible insights into how the industry operates as a whole and am grateful for this holistic insight.

Similarly, I was keen about learning how to do research, never really having done it before. The guided process by the graduation studio helped, although it proves to be mostly an autodidactic approach of trial and error until the last minute.

I am both proud of having pushed through difficulties with grappling with the challenging topic because of its wide scope as well as the research process itself. At the same time, I feel frustrated about potentially having left things on the line.