UNIVERSITY OF TWENTE

Material Passports for a Circular Built Environment

Bridging Theory and Practice on Adoption Drivers and Barriers

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Executive Summary

Problem Statement

The construction industry plays a crucial role in global climate mitigation efforts, yet it faces significant challenges in transitioning towards circularity (World Economic Forum, 2016). A main challenge in promoting circular economy practices within the linear construction economy is the need of construction stakeholders for reliable, traceable, and standardized information on building materials. As a solution to this challenge the Material Passport (MP) has been developed, a digital, multi-layered software, that delivers comprehensive, organized, and easily accessible information about the sustainability and circularity characteristics, the circular value estimation, and the circular opportunities of building materials throughout their entire lifecycle (van Capelleveen et al., 2023). By equipping stakeholders in the circular construction economy with the data needed for informed decisions on circular strategies, such as the reuse, recycling, and recovery of materials, it closes material loops and reduces the environmental impact of the construction industry. Therefore, it addresses the significant information gap between circular construction stakeholders that scholars have identified as a critical barrier towards more circular practices in the building sector (Antwi-Afari et al., 2021; Lawrenz et al., 2021; Reich et al., 2023). To the best of our knowledge, research on MP adoption has been mostly limited to research projects of MPs, from which only two had the goal of creating a MP for certain material types (Benachio et al., 2020; Göswein et al., 2022). Furthermore, adoption research so far has only focused on general MP adoption challenges, without thoroughly examining the adoption perspective of the different stakeholders across the construction life-cycles. A differentiated view of the various stakeholders is particularly important, as each stakeholder uses and informs the MP under specific conditions (Munaro & Tavares, 2021; van Capelleveen et al., 2023). Despite the progress made in formalizing the concept of MPs and identifying potential research gaps, there remains a significant gap in understanding the practical implementation and commercial adoption of this tool (Benachio et al., 2020; Munaro & Tavares, 2021; van Capelleveen et al., 2023).

With growing commercial interest, increasing regulatory requirements and the introduction of commercial MPs in the european market (*Concular*, 2023, *Digital Product Passport*, 2023, *Madaster*, 2022), this research seeks to address this knowledge gap, with the objective to shed light on the drivers and barriers associated with the adoption and implementation of MPs by the various stakeholders of the circular construction industry.

Background Information

The idea of Circular Economy and subsequently Circular Construction emerged as a response to global climate mitigation ambitions, aiming at promoting reuse, recycling, and recovery of resources in the building sector (Ellen MacArthur Foundation, 2014; European Commission, 2015). MPs have been proposed as an effective solution to provide comprehensive data about building materials, thereby facilitating their efficient use and end-of-life management (Honic et al., 2021; Munaro & Tavares, 2021; van Capelleveen et al., 2023). Recent research has emphasized the limited research focused on the adoption of MPs by the various circular construction stakeholders, indicating a clear need for further investigation (Benachio et al., 2020; Honic et al., 2021; van Capelleveen et al., 2023). Commercial applications of MPs, such as those by Madaster and Concular (*Concular*, 2023, *Madaster*, 2022), have begun to penetrate the market, bringing forth the potential to further understand existing drivers and barriers to adoption. Here, this research aims to tackle this underexplored question of MP drivers and barriers of these new software products on the market.

Research Questions

Based on the above background and problem statement, the main research question of the study is stated: **"*What are the drivers and barriers of Circular Construction Stakeholders when adopting Material Passports in practice?"*** This main question can be further broken down into six subquestions to guide the research process.

1. *What is the state of the art research on circular construction life-cycle stages and on circular construction stakeholders inside these stages?*
2. *What is the state of the art research to describe the contents of MPs to enable circular material flows?*

3. *Which circular construction stakeholders are using MPs, and for what specific informational purposes or inputs?*
4. *What is current research state on MP adoption among the circular construction stakeholders and what can it tell us about the different stakeholders perspectives towards MP adoption?*
5. *What are the barriers and drivers of MP adoption within practice?*
6. *Which stakeholders face the biggest challenges and which face the smallest challenges when it comes to MP adoption?*

Theoretical framework

This research employs a custom framework grounded in the principle that technology adoption is fundamentally driven by a balance of incentives and barriers, informed by rational actor theory. The core premise posits that stakeholders, acting as rational decision-makers, are more inclined to adopt MPs when the perceived benefits (drivers) outweigh the perceived costs (barriers) (Scott, 2000). The balance between drivers and barriers is analyzed through the lens of the Political, Economic, Social, and Technological (PEST) framework, which is particularly suitable for this study as it provides valuable insight into the complex and multi-layered nature of MP adoption, offering four comprehensive categories of analysis (Johnson et al., 2017; Aguilar, 1967). Furthermore this research approach builds on existing research efforts on MP adoption that have been using the PEST framework as the lens of analysis (van Capelleveen et al., 2023; Munaro & Tavares, 2021) (see Section 2.5).

Methodology

This study employs a mixed methods research approach to investigate MP adoption in the construction industry. The research combines qualitative and quantitative methods through online workshops with stakeholders, incorporating both open-ended interviews and Likert-scale ratings of identified drivers and barriers. An adapted Delphi method with two primary rounds is utilized: first, stakeholders participate in qualitative interviews and quantitative surveys, followed by a validation round where summarized adoption findings are presented back to participants for refinement. Purposive sampling targets individuals across different lifecycle stages who can provide detailed insights into MP adoption and use, with participants selected based on their active engagement in circular initiatives. Germany has been chosen as the study site due to its prominent role in European sustainable construction and supportive regulatory environment. The mixed methods design, guided by the PEST framework, enables both rich qualitative insights and quantifiable data while the iterative Delphi process helps validate and refine findings through stakeholder feedback (see Chapter 5).

Management Summary

The results of this thesis show that the adoption of MPs in the construction industry is uneven, with adoption dynamics differing significantly across material lifecycle stages (see Section 4.3.). Based on interviews and structured quantitative analysis, the planning and operation stages tend to emerge as the key *bottleneck stages*, while material sourcing and manufacturing show greater readiness for adoption (*facilitator stages*, see Section 6.2.).

A closer look into the bottleneck stages reveals that planning actors face considerable challenges integrating MPs into existing workflows, due to a lack of standardized data formats and limited interoperability. Particularly in Germany, complex and rigid tendering procedures further hinder the integration of MPs into project requirements. In both planning and operation, adoption is held back by the absence of regulatory obligations and high upfront implementation costs. Real estate developers reflect divergent market conditions. In the residential sector, low tenant demand and weak market incentives make MP adoption financially unattractive. In the commercial sector, however, investor-driven ESG goals, sustainability reporting, and short lease cycles create more favorable conditions for uptake (see Section 6.3.).

By contrast, the facilitator stages (material manufacturers and urban miners) tend to be more open toward MPs, valuing their potential to improve product transparency and support sustainability positioning. Their relatively advanced digital infrastructure allows easier alignment with emerging data standards. End-of-life stakeholders acknowledge the added value of traceability and reuse but still stress the need for better scanning technologies and more consistent material data to make MPs usable at scale (see Section 6.3.).

Second-life material distributors and MP providers occupy a more balanced position. Distributors view MPs as useful for verifying material provenance and quality—key to building trust in reused materials. Yet, their adoption remains limited due to weak market demand, inconsistent access to upstream data, and low institutional visibility. MP providers, while strong advocates for circularity, report challenges in onboarding diverse stakeholder groups, particularly in the absence of binding standards and interoperable digital infrastructure (see Section 6.2.).

Across all stages, fragmented data environments, economic demand, inconsistent standards, and unclear regulatory frameworks remain persistent barriers. These are especially challenging for developers, redistributors, and service providers, who must navigate high administrative burdens alongside low external demand.

The study argues that MPs are not plug-and-play solutions, but multi-stakeholder endeavors to create tailored, stakeholder-specific adoption pathways to create optimal technical, economical and regulatory frameworks. System-wide progress will depend on embedding MPs into top down regulation to ensure standardisation and integration while enabling technical sophistication to ensure interoperability and new business model unlock.

Academically, this thesis contributes an empirically grounded, lifecycle-stage perspective on MP adoption, structured through the PEST framework. It moves beyond conceptual debate by identifying specific adoption drivers and barriers across stakeholder types. Future research should examine uptake in holistic regulatory contexts, track stakeholder evolution over time, and explore the integration of MPs with digital tools like BIM and Digital Product Passports (see Chapter 7).

In conclusion, while MPs offer strong potential to advance circular construction, their success depends on resolving regulatory uncertainty, digital fragmentation, and economic risk. Addressing procedural constraints—such as restrictive tendering—will be just as critical as improving technical solutions to move from promise to practical impact.

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List of abbreviations

Abbreviation	Definition
BIM	Building Information Modelling
CE	Circular Economy
CC	Circular Construction
CO2	Carbon Dioxide
MP	Material Passport
DCC	Digital Circular Construction
DWM	Demolition Waste Management
EPD	Environmental Product Declaration
DfD	Design for Disassembly
PEST Framework	Political, Economic, Social, and Technological Framework

PU	Perceived Usefulness
PEU	Perceived Ease of Use
TAM	Technology Acceptance Model

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1. Introduction

The construction industry's pivotal role in global climate change mitigation is undisputed (World Economic Forum, 2016). Yet, despite its ecological significance and growing regulatory requirements, the industry faces substantial hurdles in moving towards a circular model of operation, which is crucial for sustainable development (Liu et al., 2021; Munaro & Tavares, 2023; Wuni, 2023). The Circular Economy (CE) model emphasizes the reuse, recycling, and recovery of materials, offering substantial potential to reduce carbon emissions, resource extraction, and waste generation, particularly within the construction sector. Nevertheless, there are many challenges impeding the construction stakeholders in adopting circular practices and business strategies.

A promising concept that has been discussed in research as an important facilitator of the shift towards more circularity is the concept of the Material Passport (MP) (Debacker & Manshoven, 2020; Honic et al., 2021; Munaro & Tavares, 2021). While MPs are conceptualized as a means to support material transparency and resource efficiency across different industries (Bai et al., 2020; Bendeković et al., 2015), this paper focuses on its application in the construction sector to assess and enhance the circularity of building components. In the context of the digital circular construction, the MP is a digital, multi-layered software that delivers comprehensive, organized, and easily accessible information about the sustainability and circularity characteristics, the circular value estimation, and the circular opportunities of building materials throughout their entire lifecycle (van Capelleveen et al., 2023). By equipping stakeholders in the circular construction economy with the data needed for informed circular decisions making, such as reusing or remanufacturing the materials (more on circular strategies in Section 4.1.), the MP addresses the significant information gap between circular construction stakeholders that scholars have identified as a critical barrier for the industries transition towards circularity. This gap has hindered stakeholders’ ability to engage effectively in circular strategies, such as reuse and recycling, thereby impeding the transition toward a more sustainable construction paradigm. (Antwi-Afari et al., 2021; Lawrenz et al., 2021; Reich et al., 2023). (Munaro & Tavares, 2021). As the pressure on the construction industry for more sustainable practices has drastically increased in recent years, MPs have gained traction in its development as a commercial product

(*Concular*, 2023, *Madaster*, 2022). Despite this, the adoption of MPs had so far experienced a limited uptake in the construction industry. Research has attributed this to a lack of comprehensive understanding of the challenges, prerequisites, and potential roadblocks linked with implementing MPs in commercial reality. (Benachio et al., 2020; Honic et al., 2021; Munaro & Tavares, 2021; van Capelleveen et al., 2023). Therefore, this research aims to delve into this knowledge gap, exploring the prerequisites and challenges through the examination of the adoption and successful implementation of MPs in the construction industry.

Study Background

There is a wide agreement among scientists that a rise in carbon dioxide (CO2) levels increases the probability for extreme weather and other irreversible changes in the natural environment. This increases the likelihood of further depletion of resources, with the consequences of wars and mass migration (IPCC, 2022). In the Paris Agreement of 2015, the countries involved agreed to try and keep the global average temperature increase to well below 2 °C compared to what it was before the industrial revolution, and also to try and limit it to 1.5 °C if possible (UNFCCC, 2015). Additionally, the year 2020 was a milestone because scientists predict that from then on, our planet will have more materials made by humans than natural biomass (Elhacham et al., 2020).

The construction industry is the world's biggest producer of CO2 and waste. It is responsible for about 25 - 40% of global CO2 emissions and only recycles 20–30% of the waste it creates when constructing or demolishing buildings (Lee et al., 2017). The industry also uses a lot of resources (35–45%) and energy (25–40%). The use of building materials is estimated to even increase significantly above these levels until 2060, unless the construction industry starts to implement more material-efficient strategies (World Economic Forum, 2016).

Due to its substantial environmental impact, the CI is one of the primary sectors where the implementation of circular strategies pose as especially relevant (Benachio et al., 2020; Norouzi et al., 2021). Therefore, the European construction industry has been under increasing regulatory pressure to improve its environmental impact by using resources more efficiently and reducing its ecological footprint (Nussholz & Milios, 2017). A clear vision to a shift away from the traditional "take, make, dispose" version of the linear economy model can be identified. Regulation wants to replace it with a system that maximizes the lifecycle of materials, minimizes waste, and fosters resource efficiency (Ellen MacArthur Foundation, 2014; IPCC, 2022). In the quest for a more circular construction industry, MPs have been proposed as an effective facilitation tool (Benachio et al., 2020; Debacker & Manshoven, 2020; Honic et al., 2021) as well as an essential policy instruments for the CE goals of the European Union (*Digital Product Passport*, 2023). As the pressure on the construction industry for more sustainable practices has drastically increased in recent years, MPs have gained traction in its development as a commercially used product in the construction sector (*Concular*, 2023, *Madaster*, 2022). Despite the progress made in formalizing the concept of MPs and identifying potential research gaps, there remains a significant gap in understanding the practical implementation and commercial application of MPs (Benachio et al., 2020; Munaro & Tavares, 2021; van Capelleveen et al., 2023). Further investigation is required to gain insights into the adoption of MPs, especially more research on understanding the prerequisites and barriers existing in the process of a MP conceptualisation from academia, given the low number of articles in this area (Benachio et al., 2020).

2. Research Design

This Chapter introduces the research aim and central research question and research goals that guide the thesis, before elaborating on the thesis outline and finally the research framework.

2.1. Research Problem

A main challenge in promoting CE practices within the linear construction economy is the need of construction stakeholders for reliable, traceable, and standardized information on building materials. This significantly hinders the stakeholders' ability to engage effectively in circular strategies, such as reuse, recycling and more (see Section 4.1.4.) (Antwi-Afari et al., 2021; Honic et al., 2021; Panza et al., 2022).

As a solution to this challenge, the concept of the MP has been developed. The MP is a digital, multi-layered software that delivers comprehensive, organized, and easily accessible information. This information covers the sustainability and circularity characteristics, the circular value estimation, and the circular opportunities of building materials throughout their entire lifecycle (van Capelleveen et al., 2023). By equipping stakeholders in the circular construction economy with the data needed for informed decisions on circular strategies, it addresses the significant information gap between circular construction stakeholders that scholars have identified as a critical barrier (Antwi-Afari et al., 2021; Lawrenz et al., 2021; Reich et al., 2023). This digital infrastructure provided by MPs is a critical facilitator for enabling circular matchmaking and the efficient reuse of materials, thereby supporting the transition from a linear to a circular materials economy.

Despite the progress made in formalizing the concept of MPs and identifying potential research gaps, there remains a significant gap in understanding the practical implementation and commercial adoption of this tool (Benachio et al., 2020; Munaro & Tavares, 2021; van Capelleveen et al., 2023). Research of MP adoption, particularly in the commercial context, is very limited. In a recent literature review by Benachio et al. (Benachio et al., 2020) only three studies were identified that developed and explored the implementation of MPs, all of which were conducted within a controlled, experimental context specific to the scientific projects. Furthermore, adoption research so far has only focused on general MP adoption challenges, without thoroughly examining the adoption perspective of the different stakeholders across the construction life-cycles (Munaro & Tavares, 2021; van Capelleveen et al., 2023).

Without a comprehensive understanding of the experiences of circular construction stakeholders when adopting MPs, it becomes challenging to understand the specific prerequisites MPs need to have for a comprehensive adoption across all life-cycle stages of a building product, thus inhibiting their development and ultimate contribution to a circular construction industry.

Therefore, this research aims to address this knowledge gap. This research aims to explore the practical drivers and barriers faced by the different stakeholders across the material life-cycle stages when adopting the MP into their practices (Benachio et al., 2020; Debacker & Manshoven, 2020; Munaro & Tavares, 2021).

2.2. Research Questions

Therefore, the main research question of the study is:

"What are the drivers and barriers of adopting Material Passports in practice among circular construction stakeholders?"

This main question can be further broken down into six sub - questions to guide the research process:

1) ***"What are the specific circular construction life-cycle stages and what are the specific stakeholders inside these stages?"***
2) ***"What are the contents of the state of the art Material Passports to enable circular material flows?"***
3) ***"Which circular construction stakeholders are using MPs, and for what specific informational purposes or inputs?"***
4) ***"What is current research state on Material Passport adoption among the circular construction stakeholders and what can it tell us about the different stakeholders perspectives towards MP adoption?"***
5) ***"What are the barriers and drivers of MP adoption within practice?"***

6) ***"Which stakeholders face the biggest challenges and which face the smallest challenges when it comes to MP adoption?"***

2.3. Research Goals and Objectives

Given the current scarcity of MP implementations and limited knowledge sharing, coupled with the lack of insights from scientific and grey literature on MP implementation in practice, this research aims to explore the adoption barriers and drivers towards MPs experienced by various circular construction stakeholders. It seeks to identify crucial factors influencing MP adoption at different life-cycle stages and recommend ways in which research and academia can support the development and implementation of MPs. By achieving these objectives, the research aims to contribute to both the theoretical understanding and practical application of MPs in the construction sector, aiding the industry's transition towards a more sustainable, circular model.

2.4. Thesis outline

Figure 1 presents a comprehensive overview of a research structure designed to investigate the drivers and barriers faced by circular construction stakeholders when adopting MPs in practice. This study is guided by a central research question that serves as the foundation for the entire investigation. To address this main question, the research is systematically divided into six sub-questions, each paired with a corresponding research step and a specific section or methodological approach. The first four questions are explored through literature research, covering topics such as circular construction life-cycle stages, stakeholders, state-of-the-art MPs, and current adoption trends. The fifth question is explored through empirical research with results presented in Chapter 5. The final question compares the challenges faced by different stakeholders in MP adoption. The research ends with the conclusions and recommendations in Chapter 7 based on the cumulative findings from all previous chapters.

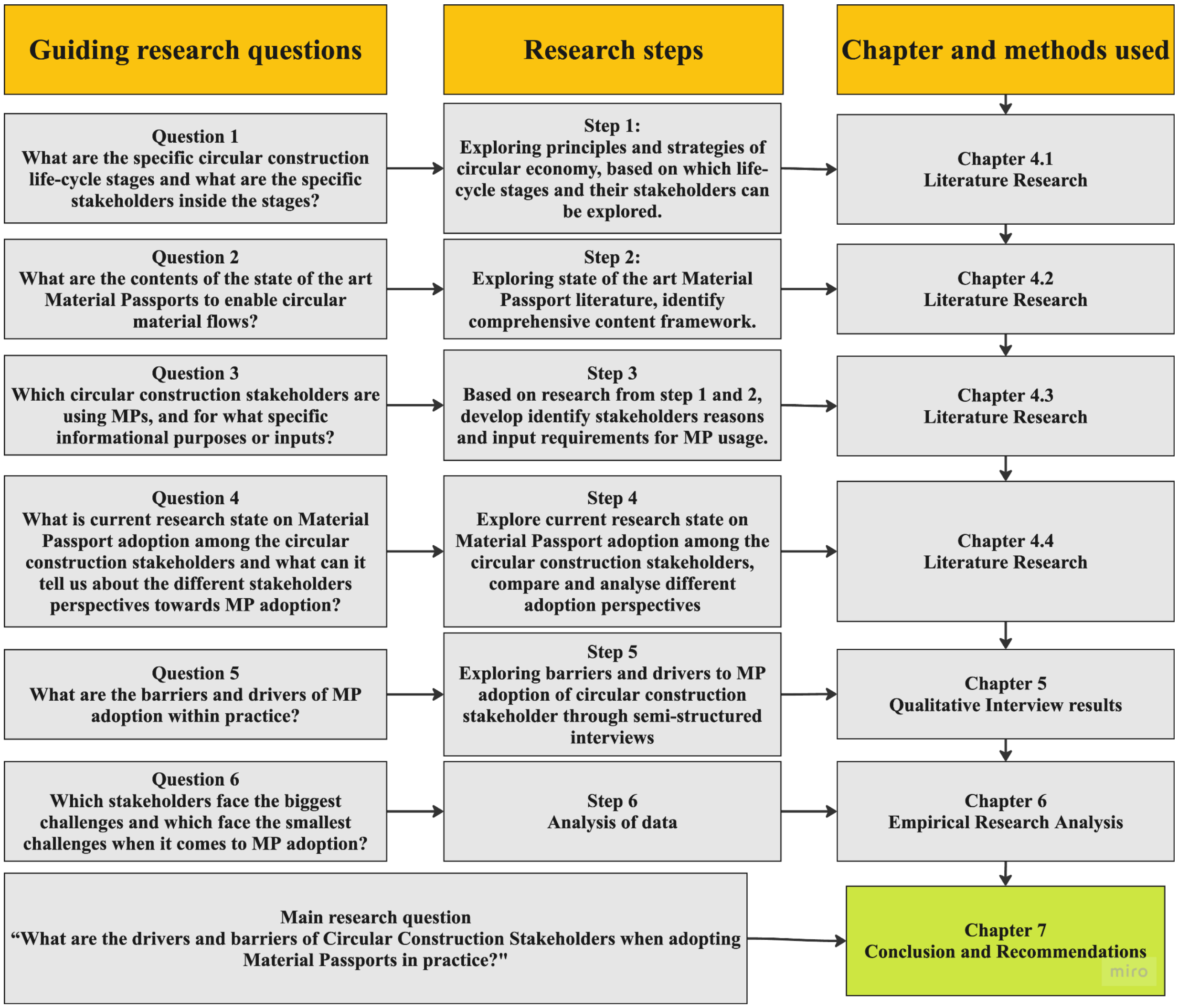

Figure 1: Thesis outline (own figure)

2.5. Research Framework

This research employs a custom framework grounded in the principle that technology adoption is fundamentally driven by a balance of incentives and barriers, informed by rational actor theory. The core premise posits that stakeholders, acting as rational decision-makers, are more inclined to adopt MPs when the perceived benefits (drivers) outweigh the perceived costs (barriers) (Scott, 2000).

The framework centers on a Driver-Barrier Balance analysis, which aims to identify and evaluate the incentives and challenges for CMP adoption across various stakeholder groups in the circular construction industry. This approach is informed by stakeholder theory (Freeman & Phillips,

2002) and its applications in construction management research (Chinyio & Olomolaiye, 2009), recognizing that adoption factors may vary significantly among different actors in the construction lifecycle.

Rational actor theory enhances this framework by emphasizing the deliberate, calculated nature of adoption decisions. However, the concept of bounded rationality is acknowledged (Simon & Others, 1972), particularly relevant in the complex realm of construction and sustainability, where decision-makers may face incomplete information and cognitive limitations.

Contextually, the framework is embedded within the principles of CE, acknowledging the unique characteristics and challenges of the construction industry in this transition (Benachio et al., 2020; Munaro & Tavares, 2023). This contextualization is crucial given the industry-specific nature of MPs and their potential role in facilitating circular practices.

The framework adopts a dynamic perspective, considering that the balance between drivers and barriers may shift over time. This temporal aspect is analyzed through the lens of the Political, Economic, Social, and Technological (PEST) framework (Blokdyk, 2018), which has been predominantly used in existing, albeit unsystematic, research on MP adoption (Munaro & Tavares, 2021; van Capelleveen et al., 2023). The PEST framework is particularly suitable for this study as it provides valuable insight into the complex and multi-layered nature of MP adoption, offering four comprehensive categories of analysis: political, economic, social, and technological factors By examining the interplay between drivers and barriers through the lens of rational decision-making, this research aims to identify key levers that could tip the balance towards MP adoption among the circular construction stakeholder group.

3. Literature review methodology

This chapter outlines the literature review methodology used to build the conceptual foundation for understanding MP adoption. It introduces the sub-questions that structure the systematic search and screening process, which are then addressed in detail.

3.1. Literature review strategy

In order to create a well-funded literature basis for the understanding of the main research question, it will be broken down into three sub-questions to not only structure the following systematic literature review approach but also ensure the comprehensive coverage of relevant aspects. The main question under investigation is:

"What are the drivers and barriers of adopting Material Passports in practice among circular construction stakeholders?"

From this, three primary research fields are delineated, each to be thoroughly examined via a comprehensive review of existing literature:

1. Drivers and Barriers to the Adoption of the Circular Economy

This research area examines the CE as a general subject of study. It introduces the foundational concepts, principles, and strategies of CE to establish a clear orientation within the broader academic field. Based on this theoretical foundation, the research then focuses on the adoption of CE practices, exploring both the drivers and barriers that influence implementation across sectors.

2. Drivers and Barriers to the Adoption of the Circular Economy in the Construction Industry

This field of inquiry investigates the adoption of CE principles specifically within the construction industry. The research places particular emphasis on the emerging topic of Digital

Circular Construction (DCC), examining how digital tools and data-driven strategies can both enable and hinder the shift towards circular practices in construction processes.

3. Material Passports in Circular Construction: Drivers and Barriers to Adoption

This topic focuses on Material Passports (MPs) as a key enabler of CE strategies in the construction sector. The research explores the role of MPs in supporting transparency, reuse, and lifecycle optimization of materials. It also identifies and analyzes the main drivers and barriers influencing the adoption of MPs in circular construction practice.

These three research fields flow logically into each other and provide the framework for the research process. This allows for a systematic and targeted literature review to be conducted.

3.2. Systematic literature review

The literature review was conducted following a structured, multi-step screening process inspired by the systematic review methodology of Tranfield et al. (Tranfield et al., 2003). In the first stage, relevant publications were identified through keyword searches and filtered using predefined inclusion and exclusion criteria to remove unrelated subject areas. In the second stage, titles were screened to assess thematic relevance, followed by a third stage in which abstracts were reviewed for alignment with the research focus. In the final stage, the full texts of the remaining publications were examined in detail, and papers were excluded if they lacked conceptual depth, empirical relevance, or a clear connection to the identified research fields. This process was complemented by a snowballing strategy to capture additional key literature. In total, 182 sources were selected for inclusion across the three thematic strands of the literature review.

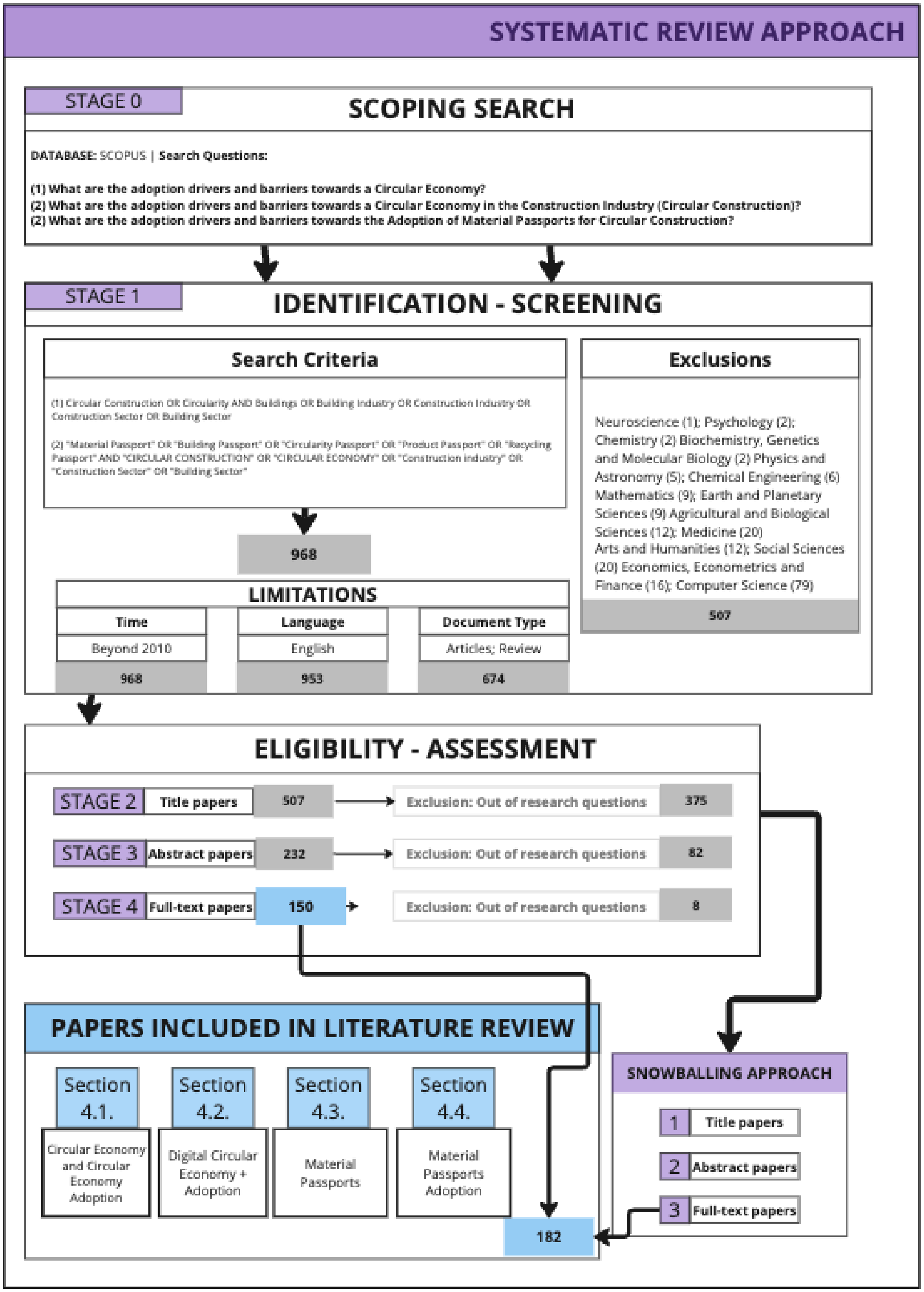

Figure 2: Systematic Literature Review Approach

4. Literature Review

This following literature review delves into the adoption of CE (Section 4.1.), starting from a broad understanding of CE, moving towards its specific application in the Digital Circular Construction Economy (Section 4.2.), progressing to the concept of MPs as a means to enhance circularity in the construction economy (Section 4.3.) and finally arriving at the review of MP Adoption (Section 4.4.).

4.1. Circular Economy

Section 4.1. introduces the historical development of the circular economy (CE), followed by an explanation of its concept, definitions, core principles, and strategies. It then examines the main drivers and barriers to CE adoption.

4.1.1. Brief History of Circular Economy

In the last two decades, the CE Model has gained increasing attention in scientific literature as a new concept and sustainable development model (Alhawari et al., 2021). The concept has its roots in various schools of thought (Ellen MacArthur Foundation, 2023). Environmental economists Pearce and Turner (Pearce & Kerry Turner, 1989) built upon the work of ecological economist Boulding (Boulding, 1966) to introduce the idea of a circular economic system. They argued that a CE, based on the law of thermodynamics, is necessary to sustain human life on earth. They identified three key economic functions of the environment: resource provision, life support systems, and waste disposal.

Other roots of CE can also be found in General Systems Theory (GST) as well as Industrial Ecology (IE). GST was proposed by von Bertalanffy (von Bertalanffy, 1950), emphasizing the interdependence and complexity of systems, highlighting the relationship between organizations and their environments. Similarly, the concept of Industrial Ecology was introduced by Robert Frosch (Frosch, 1992), as a response to the separation of industrial systems and the environment, viewing them as a joint ecosystem characterized by material, energy, and information flows. IE therefore aims to improve industrial processes through closed-loop cycles, waste management, and resource conservation.

The Ellen MacArthur Foundation also acknowledges the contributions of more recent schools of thoughts and theories, such as regenerative design, performance economy, cradle to cradle, biomimicry, and the blue economy to the development and refinement of the CE concept (Ellen MacArthur Foundation, 2023). All these developments finally lead to the current, CE model, which builds upon these concepts and applies them at an economy-wide level (Ghisellini et al., 2016).

4.1.2. Concept and Definition of Circular Economy

According to the Ellen MacArthur Foundation, unlike linear economic models that have historically relied on the principle of "take-make-dispose", CE focuses on decoupling, resource efficiency, production efficiency, slower material flows and reduced resource extraction without reducing economic activity (Ellen MacArthur Foundation, 2014). Therefore, CE is widely regarded as a systemic approach to a sustainable development (Suárez-Eiroa et al., 2019), as it is restorative by intention and is grounded in the study of non-linear systems. Figure 3 illustrates this shift by contrasting the linear and circular economic models, highlighting how CE aims to retain the value of materials and products through loops such as reuse, remanufacturing, and recycling.

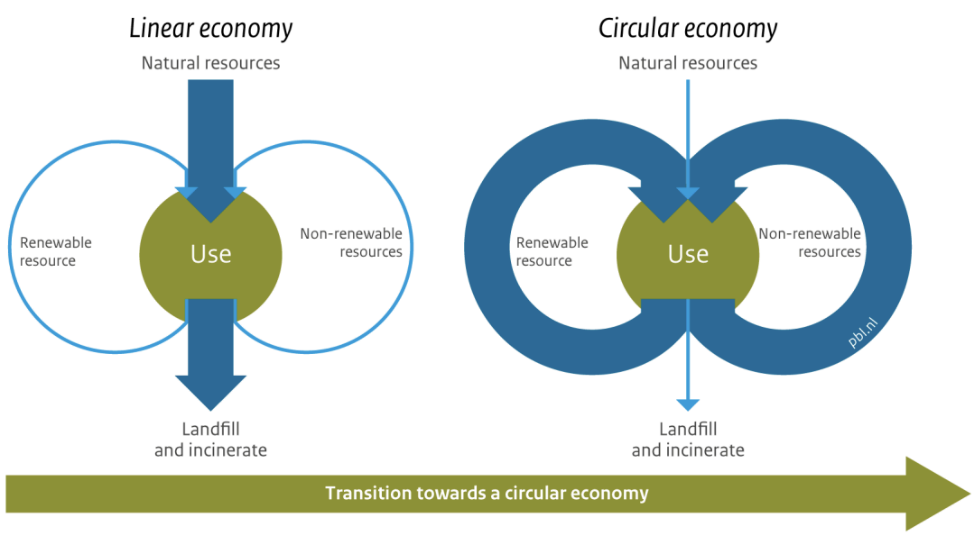

Figure 3: Comparing linear to circular economy (Source: Potting et al., 2017)

There has been a lack of consensus regarding the precise definition of CE, with various interpretations in use. Kirchherr et al. (Kirchherr et al., 2017) compiled a total of 114 definitions, to bring more clarity to the understanding of the CE. Kirchherr defines the CE as follows:

"A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (ecoindustrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations.".

Building on this definition the three core principles of the CE are introduced in the Section 4.1.3..

4.1.3. Principles of Circular Economy

Three core CE principles have been proposed by the Ellen MacArthur Foundation, that that have been widely adopted by research (Benachio et al., 2020; Ellen MacArthur Foundation, 2017):

(1) designing out waste and pollution
(2) keeping products and materials in use
(3) regenerating natural systems.

The first principle, designing out waste and pollution, focuses on the upstream innovation to prevent waste from being created in the first place, a concept extensively discussed by the Ellen MacArthur Foundation, a leading proponent of CE (Ellen MacArthur Foundation, 2017). The second principle emphasizes the importance of maintaining the value of products and materials for as long as possible, which involves strategies like reuse, repair, and remanufacturing, as highlighted in research by Blomsma and Brennan (Blomsma & Brennan, 2017). The final principle is about enhancing natural capital by encouraging flows of materials that are non-toxic and biodegradable (Geissdoerfer et al., 2017).

These principles collectively aim to create a closed-loop system, minimizing resource input and waste, emissions, and energy leakage, which is pivotal for sustainable development and has been widely advocated in academic literature (Korhonen et al., 2018).

4.1.4. Strategies for Circular Economy (R - strategies)

Another key concept of CE-oriented research is the concept of the R-strategies (also called R-principles). The R-strategies are a set of guidelines aimed at reducing waste and making the most efficient use of resources (Ellen MacArthur Foundation, 2017). They can be applied on the micro, meso and macro level, as described by Potting et.al. (Potting et al., 2017). The most basic of these is the 3R-principle, focusing on reducing, reusing, and recycling. This principle is quite well-known and has been proven to be effective in managing resources in a way that benefits the CE (Ghisellini et al., 2016).

Further components of the R-strategies evolved over time. The European Commission has added "Recover" to the model, creating the 4R framework, which is a key part of the EU's approach to waste (European Commission, 2008). As awareness of environmental issues and sustainability grew, so did the complexity and scope of the R-principles. The concept was expanded further by Yang et. al. (Yang et al., 2022), who introduced a 6R model that includes recover, redesign, and remanufacture. But the most detailed of these models is the 9R-framework, developed by Kirchherr et al. (Kirchherr et al., 2017). This framework covers a broad range of strategies. The rule of thumb here is that the lower the R-number, the more circular the approach, with R0 (Refuse) being the most circular and R9 (Recover) being the least (see Figure 4).

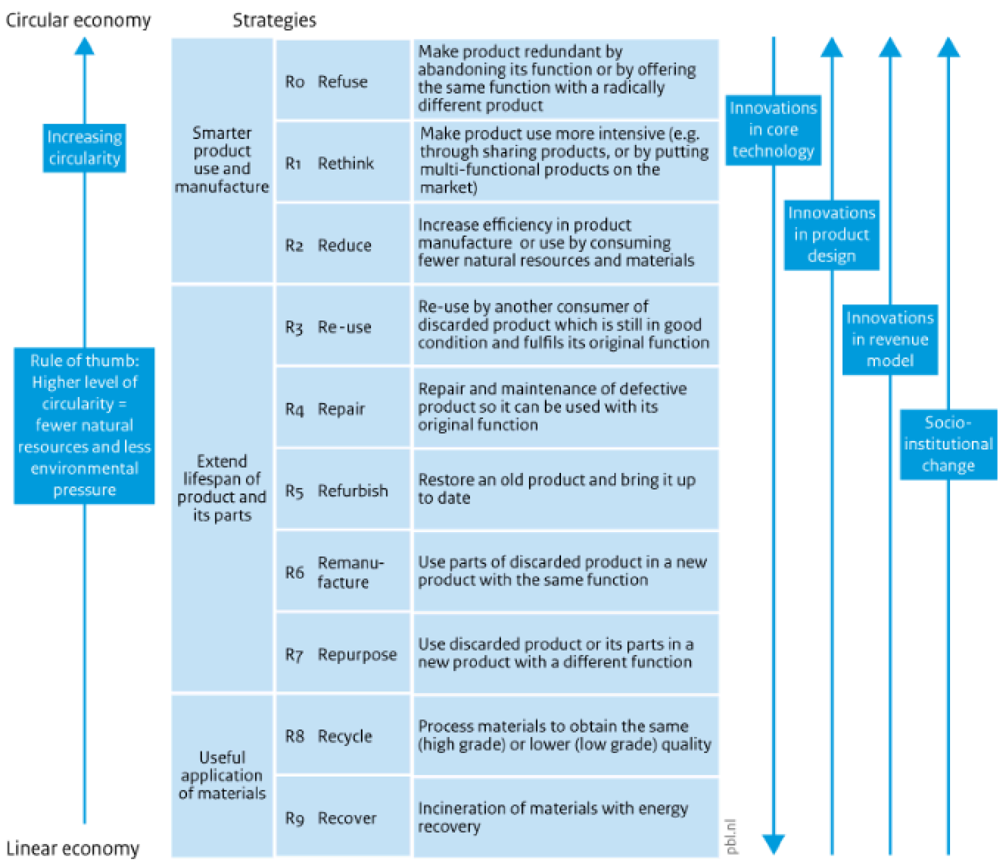

Figure 4: 9R-framework, developed by Kirchherr et al. (Kirchherr et al., 2017)

In this framework, Recycling and Recovery are closer to traditional, linear approaches but are still useful in a circular context. The strategies from R3 to R7 are about making products and parts last longer, sitting somewhere between linear and circular approaches. The top strategies, R0 to R2, focus on smarter ways to use and make products, representing the highest level of circularity. Due to its comprehensiveness the 9R strategy serves this research as a guiding framework and is adopted in the exploration of Circular Construction in Section 4.2.2.

In order to understand the application of the CE concept, principle and strategies in the context of construction, the next Section 4.1.5. will explore the different drivers, barriers and ambivalent factors of CE adoption.

4.1.5. Drivers and Barriers of Circular Economy Adoption

In the context of understanding the adoption of MPs in the construction sector, it is essential to contextualize within the broader scope of CE by considering its key drivers and barriers, as extensively discussed in literature. In a recent paper, Sarja et al. (Sarja et al., 2021) conducted a systematic literature review about drivers and barriers of CE adoption. Their work is widely cited due to its comprehensive framework, which categorizes these drivers and barriers into three distinct groups: (1) Catalyst factors, (2) Ambivalent factors, and (3) Obstructive factors. This classification provides valuable insights into the complexities surrounding the transition to CE, offering a nuanced understanding of the factors that can either promote or hinder its adoption. To further differentiate drivers and barriers of CE adoption, Sarja et al. (Sarja et al., 2021) use these categories, which have been instrumental in guiding research and practice in the field. These comprehensive three factors are introduced in Table 1 and the following text.

Catalyst Factors	**Ambivalent Factors**	**Obstructive Factors**
Environmental benefits	Governmental regulation	Uncertainty of Expectations and Outcomes
Economic and competitive advantages	Circular design and business strategy:	Linear Economic Model Embedded
Awareness of business risk	Collaboration	Shortage of Resources
Internal organisational drivers	Cultural - behavioural factors	

Table 1: Catalyst, ambivalent and obstructive factors of CE adoption, adapt from (Sarja et al., 2021)

Catalysts Factors

This category shows the factors that are clearly supporting an organization's shift towards CE.

1. **Environmental benefits:** The expected environmental benefits, are a primary driver, emphasizing the the need for sustainable resource management and waste reduction (Ellen MacArthur Foundation, 2017; Rizos et al., 2016)
2. **Economic and competitive advantages:** Further, the economic and competitive advantages such as cost savings and new business models, offer a compelling incentive

for adopting MPs, which can streamline resource use and foster innovation in construction practices (Geissdoerfer et al., 2017; Rizos et al., 2016).

3. **Awareness of business risk:** Another driver is the growing awareness of businesses about the risks associated with the linear economic models. Companies are recognizing how this traditional approach exposes them to resource price volatility and supply restrictions. This realization is steering businesses towards the CE, which promises greater stability and sustainability by reducing reliance on finite resources (Franco, 2017).
4. **Internal organisational drivers:** Lahti et al. (Lahti et al., 2018) emphasize that top management's support and company creativity, along with the capacity and commitment to change, are another important driver for businesses to develop new generation business models, highlighting the importance of leadership and innovation in driving organizational transformation.

Ambivalent Factors

This category includes factors that can either facilitate or impede the transition to CE at the organizational level, varying based on specific situations, circumstances, and contextual elements.

1. **Governmental regulation**: Kirchherr et al. (Kirchherr et al., 2018) point out the pivotal role of governmental interventions in addressing market barriers to CE. By phasing out subsidies favoring linear products and introducing policies that support circular products, such as reduced value added tax (VAT) for repairs, governments can provide a significant push towards CE.
2. **Circular design and business strategy**: A critical issue identified by Merli et al. (Merli et al., 2018) is the lack of focus on circular design and innovative strategies to slow down the consumption of materials and resources. The design phase is crucial in determining the lifespan, recyclability, and reusability of products. A failure to incorporate circular principles at this stage can significantly impede the effectiveness of CE initiatives, while innovative design can greatly enhance material and resource efficiency.

3. **Collaboration**: As Fonseca et al. (Fonseca et al., 2018) observe, intensified collaboration among companies and robust support from supply chain agents and consumers are essential for CE. This collaboration spans across various stages of the product lifecycle and involves multiple stakeholders. The strength of these collaborative efforts can either accelerate the adoption of CE practices or, if lacking, can pose a significant barrier to their successful implementation.
4. **Cultural - behavioural factors:** Ranta et al. (Ranta et al., 2018) highlight a cultural-cognitive barrier: customer preference for new products over reused ones. This consumer attitude can be a major obstacle to the reuse aspect of CE. Overcoming this barrier requires not only changes in consumer behavior but also efforts from businesses to make reused or refurbished products more appealing and acceptable to customers. This factor demonstrates how consumer preferences and market demand can greatly influence the success or failure of CE strategies.

Obstructive Factors

In transitioning towards a CE, organizations encounter several complex challenges that can influence the pace and effectiveness of this shift. Understanding these factors is crucial for navigating the transition successfully.

1. **Uncertainty of Expectations and Outcomes**: A significant barrier, as noted by Ormazabal et al. ((Ormazabal et al., 2018), is the uncertainty among companies about the tangible benefits of CE. Businesses often express skepticism regarding the cost reduction, financial profits, and long-term sustainability that CE promises. This uncertainty can significantly impede the willingness of firms to adopt CE principles, as the perceived risks and unclear outcomes may deter investment and participation in circular practices (Ormazabal et al., 2018).
2. **Linear Economic Model Embedded**: The challenge of moving away from a linear economic model is highlighted by Franco (Franco, 2017). Most industries are deeply ingrained in a linear mindset, which focuses on a straightforward 'take-make-dispose' approach. Transitioning to CE requires a fundamental shift in this mindset at the firm

level, which can be particularly challenging given the established processes, systems, and cultures that favor linear methods. This embedded linear economic model presents a significant hurdle in adopting circular practices.

3. **Shortage of Resources**: Lahti et al. (Lahti et al., 2018) point out that transitioning from a linear to a circular business model may require substantial investments. This can be a major barrier, especially for smaller firms or those with limited financial resources. The need for upfront investment in new technologies, processes, and training can be a deterrent, making it difficult for companies to commit to the transition despite understanding its long-term benefits. However, this ambition is met with several barriers.

4.1.6. Summary

In summarizing the barriers and drivers of CE adoption, it becomes evident that while significant challenges persist, the opportunities for innovation and sustainable development are equally compelling. Catalyst factors such as environmental benefits, economic and competitive advantages, awareness of business risks, and internal organizational drivers lay a strong foundation for the shift towards CE. However, the transition is nuanced by ambivalent factors like governmental regulation, circular design and business strategy, collaboration, and cultural-behavioral factors, which can either facilitate or impede progress depending on their application and context. Moreover, obstructive factors such as uncertainty of expectations and outcomes, the deeply embedded linear economic model, and resource shortages present formidable challenges that require strategic navigation.

As we conclude this exploration of CE in general, it is crucial to recognize that the principles of CE extend far beyond the theoretical, impacting various sectors in practical and transformative ways. One such sector is construction, where the adoption of CE principles holds the promise of revolutionizing material use, waste management, and sustainable development practices. Therefore, the next Section 4.2. delves into Digital Circular Construction as a specific field of CE adoption, offering a focused examination of how these overarching drivers and barriers manifest within the construction industry. This transition into Circular Construction not only highlights the sector's unique challenges and opportunities but also underscores the importance of sector-specific strategies in realizing the full potential of CE.

4.2. Digital Circular Construction

The construction industry is the largest producer of CO_2 and waste, accountable for approximately 25-40% of global CO_2 emissions and a mere 20-30% recycling rate of its waste. Therefore, there is a pressing need for sustainable change in the construction industry. The industry's substantial consumption of resources (35-45%) and energy (25-40%) only exacerbates these challenges, with projections suggesting a significant increase in material use by 2060 unless more material-efficient strategies are adopted (Lee et al., 2017; World Economic Forum, 2016). In light of these concerns and the global push for sustainability, underscored by the Paris Agreement goals (UNFCCC, 2016), the last decade has witnessed a surge in research focused on integrating CE principles within the construction sector (Benachio et al., 2020).

To tackle these pressing issues, the concept of Circular Construction (CC) has emerged as a transformative shift in the construction industry, redefining traditional approaches to sustainability, resource efficiency, and waste reduction. In recent years, this field has expanded to incorporate the critical aspect of digitalization, leading to the development of DCC. DCC represents an essential evolution of CC, as digital tools, such as MPs (discussed in Section 4.3), have become indispensable in implementing circular building strategies (Çetin et al., 2022; Heinrich & Lang, 2019; Honic et al., 2019; Singh et al., 2021; Yu et al., 2022). This Section 4.2. will examine the origins of CC and DCC within academic research, provide a clear definition and explore the different digital tools and their use in DCC. Additionally, it will outline the main lifecycle stages inside the CE for the construction sector as well as discuss the key drivers and barriers to its adoption.

4.2.1. Brief History

CC, while being considered a relatively recent term, builds on principles that have been part of environmental and sustainability discussions for decades. The concept began to gain traction in academic research in the early 21st century, as scholars and practitioners looked for ways to reduce the environmental impact of the built environment. It was not until the late 2010s, however, that the concept of CC started to emerge prominently in literature, coinciding with a global push towards sustainability and CE practices across industries (Benachio et al., 2020). A cornerstone in this evolving discourse has been the seminal work of the Ellen MacArthur Foundation, whose series of reports between 2012 and 2015 (Ellen MacArthur Foundation, 2012, 2013, 2014, 2015) have been instrumental in promoting CE concepts. Systematic literature reviews have shown that these reports, widely cited in academic and industry circles, have played a pivotal role in increasing awareness and understanding of the CE's potential benefits across various sectors, including construction (Benachio et al., 2020).

In recent years, the adoption of digital technologies (DTs) as decision support tools for CC have influenced CC research (Çetin et al., 2022; Heinrich & Lang, 2019; Honic et al., 2019; Singh et al., 2021; Yu et al., 2022). These tools provide a way to model, monitor, and optimize material use throughout a building's lifecycle, enabling more effective implementation of CE principles. DCC thus represents a significant evolution in the field, offering new methods for managing resources and reducing waste.

4.2.2. Definition

Among the first and often cited authors to focus on the CE specifically within the construction industry were Pomponi and Moncaster (Pomponi & Moncaster, 2017). Their detailed literature review revealed six dimensions essential for applying CE principles in the built environment: governmental, economic, environmental, behavioral, societal, and technological. They envision a construction industry where buildings are "designed, planned, built, operated, maintained, and deconstructed in a manner consistent with CE principles" (Pomponi & Moncaster, 2017).

Additionally, authors such as Geissdoerfer et al. (Geissdoerfer et al., 2017) suggest viewing the construction industry as a "regenerative closed-loop system" achieved through thoughtful design, maintenance, refurbishment, or reuse. In a similar vein, Leising et al. (Leising et al., 2018) promote a CE approach for buildings that adopts a "life cycle approach," aiming to extend the useful life of buildings and incorporating end-of-life considerations from the outset, effectively treating buildings as temporary material banks.

Building upon these foundational ideas, Benachio et al.'s systematic review of CC literature (Benachio et al., 2020) further refines this lifecycle perspective. They offer a definition that has been well received by subsequent research for its comprehensiveness, defining CC as:

"*the use of practices, in all stages of the life cycle of a building, to keep materials as long as possible in a closed loop, to reduce the use of new natural resources in a construction project*."

Recently, Ossio et al. (Ossio et al., 2023) have expanded upon these definitions, offering a more holistic view of CC that also incorporates the digital tools essential for its implementation in the construction industry. Their definition emphasizes the systemic nature of CC, extending beyond traditional lifecycle approaches to include enabling technologies, management systems, and policy frameworks:

"Circular Construction is a multidimensional and dynamic economic system for construction based on the application of Circular Economy principles. It aims to achieve buildings and infrastructure designs considering different systemic levels (micro, meso, and macro) to achieve a built environment that targets zero waste and pollution. It allows construction materials and products to remain in use, retaining their maximum value by following biological or technical looping strategies through and within the whole life cycle of construction projects. This approach operates in a sustainable, clean, and renewable way, allowing for the regeneration of natural systems. It is enabled by a context defined by technology, management systems, government policies and regulations, business models, and social and stakeholder behavior that enable construction needs to be met sustainably."

Ossio et al.'s comprehensive definition encapsulates the essence of CC, emphasizing not only the closed-loop use of materials but also the critical role of digital tools and systemic thinking in achieving these goals. This expanded view aligns the concept of CC with digital innovations and policy frameworks, making it a dynamic and practical solution to the environmental challenges facing the construction industry (European Commission, 2020.). The following Section 4.2.3. will take a closer look at the material life-cycle and how it contributes to creating a closed material loop within the context of DCC.

4.2.3. Life-cycle stages and R-Strategies in Digital Circular Construction

Section 4.2.3. introduces six distinct life-cycle stages of DCC. Due to the absence of a consensus on a life-cycle framework among DCC scholars, the following Section 4.2.3. will detail the rationale behind selecting these six distinct life-cycle stages for this research. This selection, underpinned by widely referenced research, aims to comprehensively capture the entire trajectory of a material from extraction to its end-of-life.

A foundational standardized framework for the life-cycle stages of construction works can be identified in the work of the Technical Committee 350 of the European Committee for Standardization (*CEN Technical Bodies - CEN/TC 350*, n.d.). This framework specifically orients itself in the standards EN 15804 and EN 15978 (Van Gulck et al., 2022). The committee proposes a four-stage modular view of the system boundaries for materials and buildings' life cycles (Dos Santos Gervasio & Dimova, 2018), which encompasses the "Product," "Construction," "Use," and "End-of-life" stages. This approach provides a structured basis for understanding and analyzing the environmental impacts of construction works throughout their entire life cycle.

Building upon this framework, this research expands the model to a six-stage life-cycle framework. This expansion serves two primary purposes: firstly, to more precisely define all areas where the nine circular strategies can be adopted (see Section 4.1.4), and secondly, to encompass all MP users (see Section 4.3.4) within the framework. The expanded framework includes: raw material extraction, manufacturing/design, construction, operation/maintenance, end-of-life, and logistics.

Separating raw material extraction from manufacturing provides a clearer assessment of how construction materials impact the environment from the moment they are sourced or recycled, compared to aggregated life-cycle analyses that combine extraction and production into a single phase. This separation allows for more strategic interventions in the supply chain to reduce the ecological footprint of construction materials (Pehlken & Baumann, 2020; Rudolphi, 2018). Furthermore, the inclusion of logistics as a distinct stage addresses its crucial role in maintaining circularity. Stark (Stark, 2015) emphasizes that careful planning for logistics is essential for optimizing material recovery and reuse from the outset of a construction project. Munaro and Tavares (2023) reinforce this point, highlighting the role of logistics in ensuring the efficient flow and recovery of materials throughout the entire process.

This six-stage model is particularly suitable for exploring the research question of MPs adoption amongst all stakeholder groups. By structuring the life cycle into these distinct stages, the MP adoption research can treat logistics and urban miners/recyclers as separate groups with their own behaviors towards MPs (see Section 4.3.4), thus expanding the scope of the research to include these important stakeholders.

In conclusion, the proposed framework includes six life-cycle stages: 1) raw material extraction, 2) manufacturing/design, 3) construction, 4) operation/maintenance, 5) end-of-life, and 6) logistics (see Figure 5). This framework is grounded in life-cycle assessment principles, the pragmatic need of DCC practices, and the recognition of logistics as an essential component in the CE model for the construction sector.

In the following part each life-cycle stage along with its complimenting R-strategies will be introduced more closely:

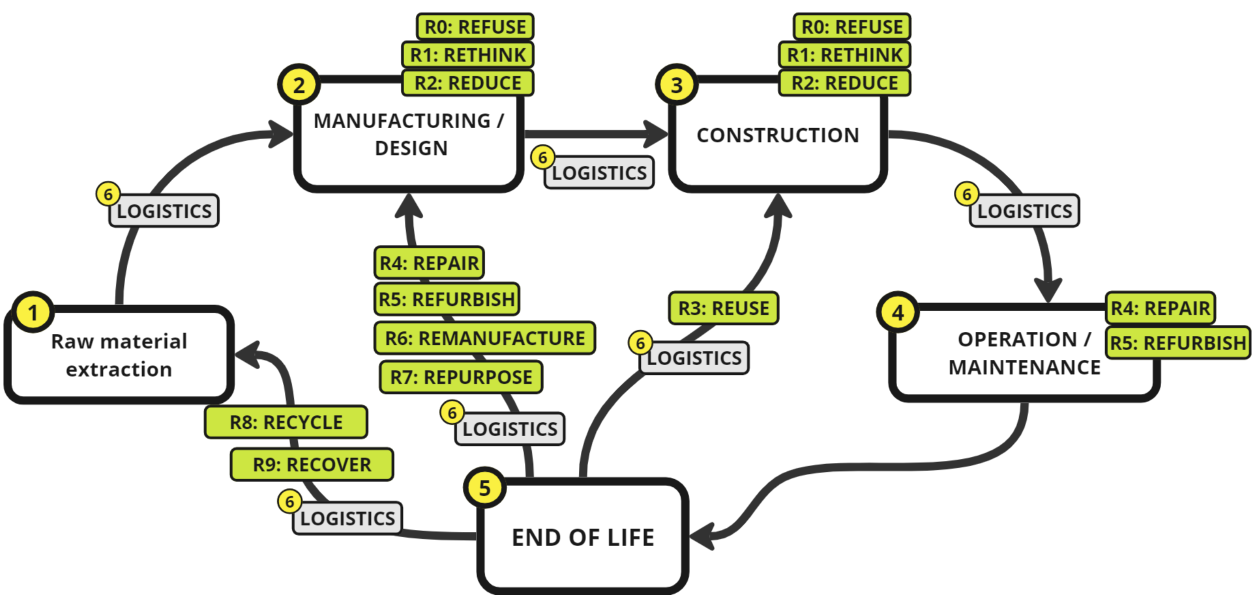

Figure 5: Life-cycle stages and R-strategies of Building Products in a Digital Circular Construction Economy (self-made)

1. **Raw material extraction:** This stage involves sourcing raw materials from the natural and built environment (urban mining), which is the starting point for the life-cycle of

construction materials. Crawford's work on life-cycle assessment underscores the environmental impact of this stage, such as resource depletion and habitat destruction (Crawford, 2011). During the first extraction of raw materials from the natural environment there is no particular R-strategy that influence this stage. If the building products life cannot be extended after their first life-cycle, R8: Recycle, or R9: Recover, are adopted here.

2. **Manufacturing/Design:** At this stage, building products are designed and raw materials are transformed into building products. During the first life-cycle of the building product this stage can apply the most high-level R-strategies: R0: Refuse, R1: Rethink, R2: Reduce. At the building and product level, environmental (energy and material efficiency) and circular design and manufacturing considerations (design for future disassembly) are crucial (Benachio et al., 2021). It is also the most important stage for prolonging the life of building products through applying the R-strategies R4-R7, therefore facilitating second life use (Benachio et al., 2020; Nussholz & Milios, 2017).
3. **Construction**: This stage represents the actual building process where materials are assembled to create structures (Crawford, 2011). The efficiency and waste produced during this stage has significant environmental impacts and can be improved through applying the R strategy R3: Reuse, as well as time and resource saving practices like offsite construction (Akanbi et al., 2018; Benachio et al., 2020)
4. **Operation/Maintenance**: This stage encompasses the use of the building and ongoing maintenance. It is pivotal for ensuring longevity and performance, as outlined by Crawford (Crawford, 2011). Here, the R-strategies R4:Repair and R:5 Refurbish can be applied through preventative maintenance (Adams et al., 2017), thus extending the life of the building (Akinade et al., 2020).
5. **End of Life**: The final stage involves the demolition, recycling, or reuse of materials. Benachio et al. (Benachio et al., 2020) and Crawford (Crawford, 2011) both emphasize the importance of planning for this stage to facilitate material recovery and minimize waste.
6. **Logistics:** Munaro and Tavares (Munaro & Tavares, 2023) highlight the importance of logistics in managing the movement and storage of materials, which is vital for efficient construction processes and later stages of reuse and recycling.

This framework, justified and supported by the stated literature, provides a holistic view of the life-cycle stages essential for implementing a CE in the construction industry. Each stage is interconnected, with decisions at one stage affecting the potential for circularity at another. Figure 5 illustrates the high interconnectedness of all 6 construction life-cycle stages, underlining how extensive and complex the implementation of the CE inside the CI is. Therefore the CI faces substantial hurdles in moving towards a circular model of operation (Liu et al., 2021; Munaro & Tavares, 2023; Wuni, 2023). Before delving into the research on the drivers and barriers of CC implementation, the next Section 4.2.4. briefly introduces the different digital tools in the DCC.

4.2.4. Digital Tools in Digital Circular Construction

DCC relies on a range of advanced digital tools that facilitate the integration of CE principles throughout the construction lifecycle. These tools play a critical role in enhancing transparency, improving resource management, and enabling efficient collaboration among stakeholders in construction projects. This Section 4.2.4. introduces the key digital tools relevant to DCC, namely Building Information Modelling (BIM), digital twins, blockchain, artificial intelligence (AI), Internet of Things (IoT), digital platforms for material marketplaces, and scanning technologies. These tools have been selected based on their demonstrated impact in facilitating CC practices and supporting the various lifecycle stages of construction, as highlighted recently by Yu et al. (Yu et al., 2022), and Çetin et al. (Çetin et al., 2022; Yu et al., 2022).

Building Information Modelling (BIM)

BIM is a foundational tool in DCC that provides a digital representation of a building's physical and functional characteristics. BIM enables collaboration among stakeholders across the building lifecycle, from design and construction to operation and deconstruction (Li et al., 2020). It integrates information on materials, structural elements, and building systems, enabling decision-making aligned with CE principles. By maintaining digital records of material properties, BIM enhances traceability and facilitates modular design, which is crucial for reuse and disassembly (Charef & Emmitt, 2021).

Digital Twins

Digital twins are virtual representations of physical assets, receiving real-time data to reflect the current status of their physical counterparts (Tao et al., 2018). They are instrumental in monitoring building performance, conducting predictive maintenance, and optimizing resource management. By providing a dynamic and real-time digital model, digital twins enable proactive interventions that extend the building's lifespan, which is essential for resource efficiency in DCC (Verdouw et al., 2021).

Blockchain

Blockchain technology offers a secure, distributed ledger that records material provenance and lifecycle data, significantly enhancing traceability and transparency in the supply chain.. Blockchain ensures that materials meet sustainability standards and are appropriately reused or recycled. When combined with other tools such as MPs, blockchain creates a reliable digital ecosystem that supports the implementation of circular principles in construction (Böckel et al., 2021; Ganter & Lützkendorf, 2019).

Artificial Intelligence (AI)

Artificial Intelligence (AI) is utilized in DCC for predictive analysis, design optimization, and identifying opportunities for material reuse. AI tools are used to assess building components, estimate the amount of reusable material prior to demolition, and offer insights for optimizing building designs to minimize waste and enhance resource efficiency (Akanbi et al., 2020).

Internet of Things (IoT)

The Internet of Things (IoT) integrates sensors into building systems to gather real-time data on resource usage, maintenance needs, and environmental conditions. IoT helps manage the building lifecycle with a focus on minimizing waste and improving circularity. By monitoring energy and resource consumption, IoT supports decision-making that promotes sustainability throughout the building's lifecycle (Sepasgozar et al., 2020).

Digital Platforms for Material Marketplaces

Digital platforms for material marketplaces are tools that facilitate the reuse of construction materials by connecting suppliers and buyers of secondary materials. These platforms promote a

CE by simplifying the sourcing of reused materials, thereby helping maintain the value of materials across construction projects (Rizos et al., 2016).

Scanning Technologies

Scanning technologies, such as 3D laser scanning, assess existing buildings and create accurate digital models that document current material conditions and quantities. These technologies are critical for identifying components that can be reused or recycled, supporting informed decisions during renovations or deconstructions (Honic et al., 2020).

Other technologies

In addition to BIM, digital twins, blockchain, AI, IoT, digital platforms for material marketplaces, and scanning technologies, numerous other digital tools have emerged to accelerate DCC. MPs also integrate many of these technologies, such as blockchain for traceability, BIM for detailed material documentation, and IoT for real-time data collection, further enhancing their role as a key enabler of DCC practices (Honic et al., 2019). However, a comprehensive review of all these technologies falls beyond the scope of this research. This thesis will focus specifically on MPs as a critical enabler of DCC, given their unique role in documenting and facilitating the reuse of materials throughout the building lifecycle. A detailed examination of MPs, including their adoption, benefits, and role in the construction industry, will be provided in the next Section 4.3 and Section 4.4.

4.2.5. Stakeholders of a Digital Circular Construction

In DCC, stakeholders collaboration gains a new importance of transforming the linear industry into a circular one. Their collective efforts, spanning from raw material extraction to end-of-life considerations, shape the implementation of circular principles within the construction industry. This comprehensive Table 2 delineates the roles and functions of key responsible actors across the aforementioned six lifecycle stages, shedding light on their contribution in the respective CC stage. For each stakeholder the respective R-strategy of their function will be explained, too.

Life-cycle stage	Responsible actor	Function in CC stage	Use of digital tools	R-strategy
(1) Raw material extraction	A1: Raw material supplier	Supplies sustainably sourced and certified raw materials that are appropriate for circular use in construction. Ensures that the materials can be reused, recycled, or safely returned to nature at the end of their lifecycle.	Implements digital traceability systems (e.g., blockchain) to ensure that sourced materials are transparent, tracked, and meet CE requirements. This ensures that materials have a verifiable chain of custody, enhancing sustainable sourcing practices.	/
	A2: Recycler / Urban Miner	Focuses on reclaiming valuable materials from waste or decommissioned structures, converting what might otherwise be debris into usable raw materials, hence supporting the recycling loop and reducing the need for virgin materials.	Uses digital platforms (such as MP) for material recovery planning, identifying reclaimed materials suitable for reuse through a central digital inventory, ensuring the efficiency of the recycling loop and maximizing resource recovery.	*R8: Recycle, R9: Recover.*
(2) (Re) Manufacturing/ Design	A3: Component designers	Designs building components that are durable, modular, energy and resource - efficient and suitable for disassembly and reuse. Ensures that components can be easily integrated into different structures and adapted to various uses over time.	Employ BIM models and MPs to enhance the reusability of components. This digital integration allows component designers to document material properties and create modular systems designed specifically for disassembly and reuse, aiding circular design principles.	*R0: Refuse, R1: Rethink, R2: Reduce.*
	A4: Component manufacturers	Gives life cycle feedback of objects (e.g. material choices) to make better product design choices for circular goals.	Utilizes digital feedback systems that capture lifecycle data through sensors embedded in components, enabling better product design choices for future iterations and ensuring compliance with CE goals.	*R0: Refuse, R1: Rethink, R2: Reduce.*
	A5: Planners (Architects/Engineers)	Produces sustainable and high-quality construction components based on circular principles. This includes the repair, refurbishing, remanufacturing or repurposing of construction materials and ensuring that the components themselves are recyclable at the end of their use.	Uses BIM and digital twins to integrate circular principles into design plans, allowing planners to evaluate different construction and deconstruction scenarios virtually, thus improving the adaptability and optimization of resource use.	*R4: Repair, R5: Refurbish, R6: Remanufacture, R7: Repurpose.*
(3) Planning/ Construction	A6: Planners (Architects/Engineers)	Develops building designs and plans that incorporate CC principles, including the planning with available second-life materials. This includes optimizing the use of resources, designing for longevity, adaptability, and future disassembly.	Adopts computational design tools that facilitate planning for reuse and designing for disassembly. BIM helps maintain a digital record of all materials, providing transparency and ensuring that each component is accounted for in future stages.	*R0: Refuse, R1: Rethink, R2: Reduce. R3: Reuse*
	A7: Construction company	Implements construction projects based on sustainable practices. Ensures that construction processes minimize waste and environmental impact, and that materials are handled in ways that preserve their value for recycling or reuse.	Implements digital material tracking using MPs to manage materials during construction. Construction companies use real-time data to ensure that materials are used efficiently, waste is minimized, and resources are available for reuse	*R0: Refuse, R1: Rethink, R2: Reduce.*
(4) Operation/ Maintenance	A8: Building Owner	Manages properties with a focus on sustainability throughout the building's lifecycle. Invests in maintenance and upgrades that prolong the life of the building and its components, supporting CE principles.	Uses digital twins for real-time monitoring and predictive maintenance of building components, which helps in extending the building's lifespan while optimizing resource use and ensuring that CE principles are embedded throughout the operation phase	*R4: Repair, R5: Refurbish*
(5) End of Life	A9: Dismantling firm	Responsible for the careful deconstruction of buildings at the end of their life, aiming to maximize the recovery of materials and	Utilizes digital deconstruction plans and MPs to identify and efficiently remove reusable components. DCC tools help dismantling	*R3: Reuse, R4: Repair, R5: Refurbish, R6: Remanufacture*

		components for reuse or recycling, thus closing the loop in the CC process.	firms maximize the value extracted from deconstructed materials, reducing waste	*, R7: Repurpose*
	A10: Redistributors of second-life materials	Manages the collection, sorting, and redistribution of used materials that are still in good condition. Provides a marketplace for second-life materials, facilitating their reintroduction into the construction cycle.	Leverages digital platforms for material exchange, connecting supply and demand for reused components. Blockchain or similar traceability technologies are used to ensure the authenticity and quality of the materials being reintroduced into the construction cycle.	*R3: Reuse, R4: Repair, R5: Refurbish, R6: Remanufacture, R7: Repurpose, R8: Recycle, R9: Recover.*
(6) Logistics / Reverse Logistics	A11: Logistics Firm	Specializes in the transportation and handling of materials throughout their lifecycle, including the reverse logistics of returning materials for reuse or recycling. Ensures efficient, safe, and environmentally responsible logistics operations.	Uses digital logistics management systems to track the movement of materials, enabling efficient and environmentally responsible logistics. Reverse logistics are supported through data-driven planning tools that optimize routes and manage inventory for second-life materials.	/

Table 2: MP Stakeholders (Böckel et al., 2021; Charef, 2022; Hansen et al., 2012; Kanters, 2020; King et al., 2023; Munaro & Tavares, 2023)

4.2.6. Drivers and Barriers of Digital Circular Construction

This Section 4.2.6. focuses on the comprehensive analysis of drivers and barriers to CE adoption in the construction sector, primarily utilizing the framework developed by Munaro and Tavares (Munaro & Tavares, 2023) in the review of scientific literature about the CC and DCC adoption. After a content analysis of 47 CC and DCC adoption papers, five adoption categories were used: (1) economic, (2) informational, (3) institutional, (4) political, and (5) technological. This comprehensive and structured approach will be used to introduce the multifaceted barriers and drivers associated with CE implementation in the built environment and finally transferred to explain the need for the development of MPs. The following Table 3 shows an overview of the drivers and barriers:

Category	Themes related	Barriers	Driver
1. Economic	Economic / Financial / Market	Unfavorable material market economics	Business opportunity of circular business models
		Lack of financial aid	
2. Informational	Informational / Socio Cultural	Lack of awareness, knowledge, and circular initiatives in society	Measures to support CC research, education and information

3. Institutional	Institutional / Organizational	Lack of knowledge, integration, and cooperation between stakeholders	Improved stakeholder awareness, integration, and information
4. Political	Political / Regulatory legislative	Lack of government policies, regulatory instruments, and fiscal actions	Establishment of a governance plan
5. Technological	Technological / operational / management	Lack of technologies and infrastructure	Development of tools and technologies that promote circular buildings

Table 3: Barriers and Drivers of CC adoption in 5 different categories (source. Munaro and Tavares, 2023)

1. Economic Drivers and Barriers

Economic Drivers:

Incentive of circular business models: This driver stresses the incentive for circular business models that a CE marketplace could create in the building sector. Starting with the creation of physical or online marketplaces, incentive and assurance schemes for more reuse and/or recycling, as well as the economic possibilities of the underlying data economy as well as new circular building techniques. Economic incentives are crucial for promoting CE adoption, highlighting the importance of establishing markets for secondary materials and ensuring their financial viability (Adams et al., 2017), (Ghisellini et al., 2016)

Economic Barriers:

The economic barriers to business grants include the abundance and affordability of new raw materials, insufficient market mechanisms for material recovery/reuse, high costs associated with deconstruction and material processing, overpriced recycled materials, lack of incentives for Construction and Demolition Waste (CDW) management, and the failure of product pricing to reflect environmental costs (Akinade et al., 2020; Aslam et al., 2020; Ghisellini et al., 2016). Other economic barriers stem from a lack of financial aid include a hesitancy to invest in circular business models due to perceived financial risks, a prevailing expectation of quick returns and the premium costs associated with green buildings, the substantial expenses involved in developing product certifications, and the hefty initial investment required for waste technology (Andersen et al., 2019; Charef & Emmitt, 2021; Hart et al., 2019)

2. **Informational Drivers and Barriers**

Informational Drivers:

Improve CE awareness and research: the increasing awareness through electronic media, CE campaign and research poses as a significant informational driver, which is essential for fostering a broader understanding and acceptance of CE principles (Adams et al., 2017; Bilal et al., 2020).

Informational Barriers:

Lack of research, education, and information: A critical barrier to CE adoption is the widespread lack of awareness and understanding of CE principles among stakeholders, showing in the lack of publicity and limited environmental management programs and facilities at institutions (Aslam et al., 2020; Ghisellini et al., 2018).

3. **Institutional Drivers and Barriers**

Institutional Drivers:

To advance DCC, it is essential to implement strategic measures: conducting pre-demolition audits to minimize waste, fostering a culture of on-site waste sorting and processing, and encouraging the reuse and upcycling of materials. Strengthening connections between demolition contractors and material suppliers can further promote the salvage of valuable resources. Additionally, benchmarking recovery and resale efforts of secondary materials will drive market competition and diversity. Establishing clear roles and fostering long-term collaborations among stakeholders, coupled with targeted training in CE principles, can significantly enhance sustainable construction practices. (Antwi-Afari et al., 2021; Aslam et al., 2020; Mahpour, 2018; Nussholz & Milios, 2017)

Institutional Barriers:
Circular construction adoption faces institutional barriers such as entrenched supply chain conservatism, a prevailing ownership mindset over service utilization, gaps in knowledge about Design for Disassembly (DFD), green design, and end-of-life products, as well as a deficiency in awareness about circular tools like Environmental Product Declarations (EPDs) and MPs. Additionally, there is an underutilization of the waste hierarchy, favoring recycling over other strategies, and a lack of comprehensive guidelines and tools for circular buildings' implementation and assessment (Akinade et al., 2020; Andersen et al., 2019; Charef & Emmitt, 2021; Ghisellini et al., 2018; Mahpour, 2018)

4. **Political Drivers and Barriers**

Political Drivers:
Public financial aid is instrumental in advancing the CE within the construction sector, entailing the development of strategic action plans at national to local levels with clear goals and targets. This includes government incentives to stimulate the industry, such as subsidies for shared facilities, and financial support for innovation, research, and technology adoption in circular practices. Embedding circular procurement criteria, establishing producer responsibility, and incentivizing environmental performance through policy credits are key measures to enhance industry engagement in circularity (Bilal et al., 2020; Hart et al., 2019; Mahpour, 2018; Nussholz & Milios, 2017).

Fiscal and regulatory measures are pivotal for promoting the CE, focusing on reducing greenhouse gas emissions through enforced metrics for building materials. A regulatory framework overseeing construction and demolition waste management, with mandatory reporting, complements fiscal strategies such as tax reductions for labor, increased taxation on virgin materials, and exemptions for goods made from secondary materials. Enforcement through penalties for non-compliance, alongside incentives for adherence to CE regulations, and increased landfill charges, further underpins these actions (Aslam et al., 2020; Ghisellini et al., 2018; Hart et al., 2019).

Political Barriers:
The adoption of CC is impeded by a spectrum of political barriers. Challenges include inadequate incentives for end-of-life design and Design for Disassembly (DfD), rigid building codes, lack of Environmental Product Declarations (EPDs) standardization, and a deficit in producer responsibility for resource management. Additionally, the sector grapples with an absence of a tax framework for reclaimed materials, no mandated minimums for reusing and recycling construction and demolition waste, and suboptimal land-use zoning, which overlooks the principles of resource circularity and sustainable urban planning. Furthermore, CC adoption is obstructed by the absence of national goals with binding effects, insufficient support for research and business strategies, inadequate government supervision due to a lack of resources and expertise, and ineffective management of Construction and Demolition Waste (CDW). (Akinade et al., 2020; Al Hosni et al., 2020; Andersen et al., 2019; Charef & Emmitt, 2021; Ghisellini et al., 2018; Mahpour, 2018; Williams, 2019)

5. Technological Drivers and Barriers

Technological Drivers:
The technological drivers in circular building involve creating spatial usage plans, enabling component recovery through planned disassembly, and enhancing buildings' adaptability and disassembly through prefabrication. Mandatory sorting and CDWM plans will improve resource management and market competition. An integrated information system is crucial for tracking material stocks and markets, with BIM as a tool for component tracking and EPDs and MPs becoming essential as circularity progresses (Aslam et al., 2020; Nussholz & Milios, 2017; van Bueren et al., 2019).

Technological Barriers:
The technological advancement of CC is currently restricted by inadequate separation of materials, logistical difficulties, and the lack of standardized disassembly processes. The shortage of tools for identification, classification, and certification of reclaimed materials, coupled with the inherent complexity of materials and building structures, obstructs effective Design for Disassembly (DfD) practices. Such challenges undermine the efficacy of Construction and Demolition Waste (CDW) management. Moreover, the industry grapples with a deficit in effective green building design development and faces significant hurdles regarding data quality and availability, which is compounded by concerns over privacy, trust, ownership, and access. Complications in comprehending and developing Environmental Product Declarations (EPDs) also reflect the overarching absence of an integrated information management system, which is crucial for driving the circular economy. This information gap is a critical barrier, impeding stakeholders' ability to engage in material reuse, recycling, and other circular strategies, thus inhibiting the transition towards a more sustainable construction paradigm. (Akinade et al., 2020; Andersen et al., 2019; Giorgi et al., 2022; Lawrenz et al., 2021; Liu et al., 2021; Williams, 2019)

4.2.7. Summary

The adoption framework developed by Munaro and Tavares (Munaro & Tavares, 2023) provides a structured lens for analyzing the conditions under which Digital Circular Construction (DCC) practices—such as the use of Material Passports—can be effectively implemented. It highlights the pressing need to employ new information management systems into the CI to address significant technological, informational and management barriers in the promotion of DCC. The technological drivers and barriers shed light on the problem of insufficient technologies and infrastructure for the realization of DCC practices. Furthermore, the institutional barriers mention the lack of knowledge and guidelines for using technology tools such as a MP but also challenges in organizational implementation and acceptance of such systems.

The complexity and diversity of these technological barriers underscore the necessity for an advanced solution that serves the need for a reliable, traceable, and standardized information on the material composition of buildings for all participants of each life-cycle stage for effective reuse and recycling (Antwi-Afari et al., 2021; Honic et al., 2021; Panza et al., 2022). Therefore, the concept of the MP has gathered widespread scholarly interest due to its theoretical possibility to be one essential solution towards solving these technological problems (Debacker & Manshoven, 2020; Honic et al., 2021; Munaro & Tavares, 2021; van Capelleveen et al., 2023).

Therefore, the subsequent Chapter 4.3. will delve into the MP concept in detail. They will illustrate how its development, application, and the resulting benefits can significantly support the construction industry in its endeavor to achieve a CC practice.

4.3. Material Passports

MP have become a crucial tool in research, enabling various stakeholders in material-intensive industries to make informed circular strategy decisions by providing them with essential information. The following Section 4.3.1. will describe the concept and definition of MP, before delving deeper into the most recent research of the content of the MP. After this, the stakeholders of MPs in the context of the CI will be introduced, before finally arriving at the adoption research surrounding MPs in the CI, thus summing up the literature review.

4.3.1. Terminology

The concept of the MP has gathered widespread scholarly interest due to its versatility and application across various research perspectives, product types and industries. This interest is reflected in the diversity of terms used to describe similar concepts, such as "Product Passport," "Building Renovation Passport," "Building Passport," "Resource Passport," and "Life-cycle Passport." The terminological analysis by Capelleveen et al. (van Capelleveen et al., 2023) highlights the difficulty in pinpointing the exact origins of the MP - term. The earliest documented mention is found in a paper by McDonough and Braungart (McDonough & Braungart, 2003), although a similar idea, termed a "building renovation passport," was described by Eichstädt as early as 1982. This early instance demonstrated the concept's potential to focus on specific life-cycle stages within the construction industry.

Initially, the term "Product Passport" and "Material Passport" were used somewhat interchangeably, with subtle distinctions in their scope and application. Over time, "Material Passport" became the preferred term, especially when emphasizing the material composition and lifecycle of products. "Product Passport" suggests a broader range of information, encompassing not only material details but also lifecycle, usage, and end-of-life considerations (van Capelleveen et al., 2023).

Beyond the construction sector, the concept's relevance extends to fields such as the battery and shipping industries, underscoring its broad applicability (Bai et al., 2020; Bendeković et al., 2015). Nevertheless, the following exploration of the MP concept will concentrate on its application in the CI. Furthermore, this research will focus on the most prevalent form of MPs, which aims at a comprehensive circular optimisation and facilitation of construction products and materials across all building life-cycle stages (see Section 4.2.3).

4.3.2. Definition

The development towards a comprehensive definition of the MP concept has been shaped by various contributions over time. Prior to a unified definition proposed by van Capelleveen et al. (van Capelleveen et al., 2023), several definitions garnered significant attention within the academic community, each contributing to the evolving understanding of MPs. Early interpretations of MPs, such as those by McDonough and Braungart (McDonough & Braungart, 2003), focused on the detailed composition of products and their potential for material reuse and recycling. This view emphasized the intrinsic value of products beyond their initial use phase, advocating for a design philosophy that enables a sustainable lifecycle management approach. Another perspective, as outlined by Eichstadt and later by Hansen et al. (Eichstädt, 1982; Hansen et al., 2012), placed MPs within the broader context of a building product's entire lifecycle. This approach highlighted the necessity of capturing and managing data from design and manufacturing to use and end-of-life, underscoring the significance of optimizing each phase for environmental sustainability. Further definitions, such as those proposed by Debacker and Manshoven (Debacker & Manshoven, 2020) and Honic et al. (Honic et al., 2021), portrayed MPs as pivotal tools for enabling informed decision-making that aligns with the principles of circularity. By offering access to comprehensive product information, these perspectives underscored the role of a MP to facilitate the identification of opportunities for extending the product life, enhancing resource efficiency, and mitigating environmental impacts. Van Capelleveen et al. (van Capelleveen et al., 2023) analyzed and synthesized these diverse definitions and proposed a refined definition:

"a material passport (or product passport) is a digital interface composing a certified identity of a single identifiable product by accessing the set of life cycle registrations linked to this object in order to yield insight into the sustainability and circularity characteristics, the circular value estimation, and the circular opportunities for both that product and its underlying components and materials."

This definition emphasizes the digital and interactive nature of MPs, their focus on individual products, and their comprehensive coverage of lifecycle data. It highlights the role of MPs in facilitating a deeper understanding of sustainability and circularity, thereby supporting informed decision-making throughout the supply chain. It therefore will serve this research as the guiding definition.

4.3.3. Contents of Material Passport

MPs represent an innovation within CC, providing sustainable resource management pathways in industries like construction. These digital tools provide vital data about materials and products to the circular loop stakeholders, streamlining their identification, recovery, and recycling processes. However, interpretations of the content of MPs have varied, shaped by the specific uses they are intended for.

The evolution of MPs has seen various researchers contribute to our understanding of what they should contain. Göswein et al. (Göswein et al., 2022) emphasized the importance of detailed material composition information to enable accurate identification and potential reuse. Cetin et. al. (Çetin et al., 2022) pointed out the role of MPs in recording material quality and origins, advocating a database-centric approach, while Honic et al. (Honic et al., 2019) promoted the inclusion of lifecycle data, suggesting MPs should be updated throughout a building's lifecycle. Hansen et al. (Hansen et al., 2012) explored MPs as repositories for information that could underpin new business models within the CE framework.

Van Capelleveen et al. (van Capelleveen et al., 2023) synthesized these diverse perspectives into a multi-layered content model for MPs. Their structured approach delineates three categories of information that MPs should include and therefore differs from other existing models. The following part will give a closer explanation of each respective layer of the content framework. The model breaks down the content of the MP into three dimensions, which then are further differentiated into other subcategories. After an overview (Figure 6) the content of the subcategories are explained in more detail.

THREE LEVELS OF A MATERIAL PASSPORT			FUNCTION
1. DATA ELEMENTS			Registration of the object and/or its sub-components
1.a. Object Characteristics	1.b. Technical Reports	1.c. Official Declaration	
2. PERFORMANCE INDICATOR			Translation of the object in environmental performance indicators
2.a. Official (mandated) certificates		2. b. Personal Indicators	
3. INTERACTIVE DECISION SUPPORT TOOLS			Understanding the effects of alternative product governance strategies on CE objectives
3.a. Various digital tools to support circular decision making			

Figure 6: Multi-layered content framework of MP (van Capelleveen et al., 2023)

1. **Data Elements**
    a. Object Characteristics: Essential details about the object or its sub-components, including the quality of the components, the expected lifespan, the valuation of use, recovery and reuse value, the separability, etc.
    b. Technical Reports: Documents covering the physical composition (size, volume, density, format, etc.) and technical characteristics (architectural drawings in BIM format: geometry, spacial relations, locations), dismantling guidelines, safety guidelines, etc.
    c. Official Declarations: Serving history, contracts, Geo-Info, List of hazardous substances.
2. **Performance Indicators:**
    a. Official (mandated) certificates: Energy Performance Certificate (EPC´s), Environmental Product Declarations (EPD`s), General Ratings like Leadership in Energy and Environmental Design (LEED), etc.
    b. Personal Indicators: Life-Cycle Analysis (from ISO LCA), CE indicators, Recycling Indicators, Circularity Indicators, etc.
3. **Interactive Decision Support Tools:**

a. Digital tools to aid in understanding the environmental impact of the object and to inform decisions about its end-of-life options, recycling, or reuse potential like guiding options for repair and renovations, scenario modeling tools, etc.

The framework by Van Capelleveen et al. (van Capelleveen et al., 2023) recognizes the complexity and multi-layered nature of MPs. It calls for a systematic approach that encompasses thorough data -collection, -management and -translation and a CE decision making support, which adapts as the object progresses through its lifecycle. The model encompasses all pre-existing research and therefore sets the currently highest standard for the scope and depth of information included in MPs.

The content of MPs is fundamental to their role as facilitators of CE. As the CC life-cycle visualization in Section 4.2.3. has shown, the MP needs to bring together many different stakeholders along the circular product value chain. Moving forward, the following Section 4.3.4. will explore the different stakeholders involved in the circular life-cycle of a product.

4.3.4. Stakeholders/Users of Material Passports

Section 4.2. has shown the increased complexity of a CC value chain as the industry progresses from a linear economic model into a circular economic model. The institutional barriers towards CC implementation consist of the lack of knowledge, integration and cooperation between the various stakeholders of the CC value chain. Among the technological barriers is the lack of data infrastructure to provide the facilitation of necessary information that enable CE - decisions for stakeholders. In this context, digital solutions like MPs have become essential to bridge the various barriers towards CC implementation. As MPs can provide the data infrastructure for the governance of the entire product life cycle, this Section 4.3.4. introduces the involved actors, their role and perspectives toward MPs. For the purpose of this analysis, stakeholders are considered as the users of Material Passports, even though they are not always the ones directly interacting with the tool (e.g., building owners). However, since they are ultimately the responsible decision-makers for MP adoption in their respective stage, they are treated as the relevant user group in this study.

As this research focuses on the operational adoption of MPs, the further exploration of the MP stakeholders will exclude the external stakeholders (product regulation stakeholders) and only look at the stakeholder group essential to the product life-cycle process (product operation stakeholders) (King et al., 2023). The life-cycle stages and the stakeholder model from Section 4.2.3. will serve this exploration as orienting models. Following the aforementioned argumentation about CC´s need for facilitating data infrastructure, as an additional category the category "7. Material Information Exchange" will be added to encapsulate those actors providing the data infrastructure and information flow.

Figure 7 visualizes how the different CC stakeholders use the information of the MP to realize circular strategies (see Section 4.1.4.) and what kind of informational input is needed by each stakeholder to provide the ability for circular decision making for other stakeholders further down the material life-cycle. The arrow from the MP towards the stakeholder group represents the information used by a respective stakeholder for his CC purposes. The arrow from the stakeholder group towards the MP represents the information input performed by the stakeholder.

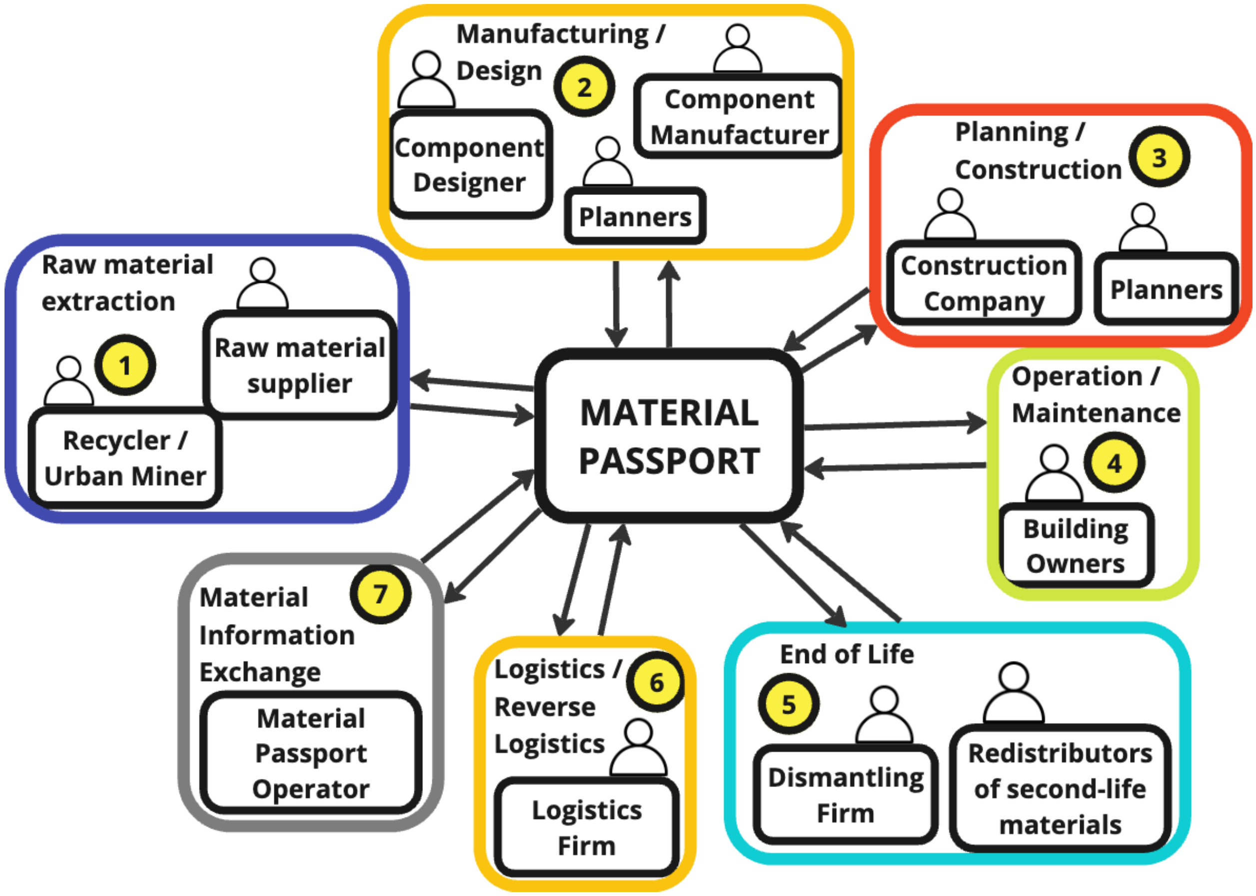

Figure 7: Visualization of the Stakeholder relationships towards MPs

The specific content of the informational use or input is described in the following Table 4. Here, every single relationship between a CC actor towards the MP is introduced in detail.

Life-cycle stage	CC actor	Type of MP use by actor	Type of MP input by actor
(1) Raw material extraction	A1: Raw material supplier	Utilizes MP data to improve their sourcing strategies based on feedback from downstream users about material performance and sustainability metrics.	Inform MP on the origin, composition, and environmental impact. This transparency helps in making informed decisions later in the life cycle about reuse or recycling.
	A2: Recycler / Urban Miner	Use of MP for transparent data elements information about object/object components to identify circular potentials and enhance sorting efficiency. Use of MP for resource recovery planning as MP provides data on quantities of material that can be regained at a certain time.	Inform MP with detailed guides for product disposal will enable better, safer and more efficient waste Management. Informs MPs with information on materials recovered, processed, and their condition.
(2) Manufacturing / Design	A3: Component designers	Use data elements and performance decisions, and decision making support tools for CE-based design decisions, ensuring compatibility with existing materials and systems. Use MPs to understand the life cycle impacts of different materials and integrate this knowledge into eco-friendly design practices.	Inform MP with data on object characteristics and technical support.
	A4: Component manufacturers	Access to data elements of used materials and object components for CE-based manufacturing decisions, Verification of the sustainability credentials and origin of raw materials from suppliers. Uses MPs to ensure that the materials chosen meet environmental and building standards, and to stay updated on the latest innovations in sustainable materials.	Create a new single identifiable product in MP when producing materials and inform it with all necessary data elements and performance indicators like materials used, chemical contents, expected lifespan, recycling instructions etc..
	A5: Planners (Architects/Engineers)	/	Give life cycle feedback of objects (e.g. material choices) to improve CE-based product design.
(3) Planning/ Construction	A6: Planners (Architects/Engineers)	Use MP to assess available second-life materials for building planning, use MP decision-making support tools for easy	Adds detailed information on the usage of materials and components within the architectural or engineering plans, including

		deconstructability, for planning with efficient resource use, planning with low CO2 emissions and for future reuse. Uses MPs to ensure that the materials chosen meet environmental and building standards, and to stay updated on the latest innovations in sustainable materials.	placement, exposure conditions, and integration with other materials or systems
	A7: Construction company	Use of data elements information of building materials for assembly and installation processes to enhance material traceability and management.	Inform MP with actual on-site usage data of materials and components, including any deviations from planned use or unexpected conditions that might affect future reuse or recyclability. Uploads technical characteristics (BIM models, including connection details, material location etc.) and official declarations (geo information, hazardous substances, etc.).
(4) Operation/ Maintenance	A8: Building Owner	Use of interactive decision support tools of MP to manage the building efficiently during its use phase, and to plan for eventual material recovery and building deconstruction. Consults MPs to make informed decisions about maintenance, renovations, or retrofitting to maximize the building's lifecycle value.	Inform MP about ongoing maintenance records, renovations, and any changes made to the building that affect the materials or their potential for reuse, ensuring this data is reflected in the MP.
(5) End of Life	A9: Dismantling firm	Uses MPs to plan and execute the deconstruction of buildings in a way that allows for the highest rate of material recovery and reuse.	Provides detailed records of how materials were dismantled or deconstructed, including the condition of materials post-dismantling, to help inform their suitability for reuse or recycling.
	A10: Redistributors of second-life materials	Use MP to valuate second life products and to handle procurement flows more efficiently, utilizing MPs to accurately describe the materials available for resale or reuse, providing potential buyers with detailed information on material history and quality.	Inputs information regarding the condition, history, and any treatments or modifications that second-life materials have undergone before being redistributed.

(6) Logistics / Reverse Logistics	A11: Logistics Firm	Use MP to handle and transport materials appropriately, including information on packing, storage, loading/unloading, etc.	Inform MP with life-cycle data like location data for tracking of the reverse logistics processes.
(7) Material Information Exchange	A12: Material Passport Operator	Use feedback from users of MPs to continuously improve the functionality, accessibility, and value of the passports.	Ensure optimal data availability, decision-making support tools and optimal interoperability for all involved actors in all stages of the CC life-cycle. Add missing information on materials from the internal data-bank and using AI.

Table 4: CC actors behavior towards MP (Böckel et al., 2021; Bouwend Nederland, 2020; Debacker et al., 2016; Hansen et al., 2012; Kanters, 2020; King et al., 2023; Makarova et al., 2021; Munaro & Tavares, 2023; van Capelleveen et al., 2023)

By providing a comprehensive overview of the relationships between stakeholders and MPs, this Section 4.3.4. has laid the foundation for a closer understanding of how the different stakeholders can use the information MPs to realize circular strategies (see Section 4.1.4.) and what kind of informational input is needed by each stakeholder to provide the ability for circular decision making for other stakeholder further down the material life-cycle. It also has helped clarify the roles and interactions of various stakeholders at different life-cycle stages, providing a solid base for understanding their impact on promoting a sustainable construction environment.
Furthermore, the analysis underscores the presented findings about the barriers of CC implementation in Section 4.2.3., as it exemplifies the fragmented knowledge bases and inadequate data infrastructure (institutional and technological barriers) hindering the CC realization.
Looking ahead, it is important to explore in more detail the specific barriers and drivers that affect the adoption of MPs. The upcoming section will consider both general and stakeholder-specific factors that influence MP adoption. This detailed examination will yield practical insights that are critical for better understanding MP adoption.

4.4. Material Passport Adoption

Section 4.4. focuses on the adoption of MPs among stakeholders in the CC industry. Section 4.4. provides a comprehensive analysis of the barriers and drivers that impact the adoption of MPs and assign them to each responsible actor in the CC lifecycle, based on their described functions in the CC life-cycle, as shown in the previous Section 4.2.3.. Understanding the unique challenges and incentives each stakeholder faces will allow to create a comprehensive basis for the MP adoption research. As the MP is a CE facilitation tool, it can be hard to find the exact line to distinguish between adoption challenges posed to the circular building economy in general and those challenges that specifically apply to the adoption of MPs. Nevertheless, the task of distinguishing between the two will be attempted in the following analysis.

The literature review has identified two studies focusing on the adoption challenges of MPs. The first study, conducted by Munaro and Tavares, divided the challenges of MP adoption into three key areas: political, commercial, and social (Munaro & Tavares, 2021). The second study by van Capevelleen et al. offered a more detailed examination, expanding the categorization of challenges to include four dimensions: technological, economic, political, and socio-temporal (van Capelleveen et al., 2023). When looking at the adoption drivers of MP, the literature review has identified 4 studies focusing on the adoption challenges

For the following analysis, the extended classification by van Capelleveen et al. will be used. It provides a deep insight into the complex and multi-layered nature of MP adoption, as the classification includes four categories of analysis, namely technological, economic, political and socio-temporal. While van Capelleveen et al. analysis only focuses on the challenges of MP adoption, the following approach will also encompass the drivers towards MP adoption of each respective category while also linking them to the respective stakeholder group as shown in the previous Section 4.2.3., therefore providing the first analysis of this kind. Here, only the directly affected stakeholders for each driver or barrier will be listed. This distinction will help clarify the primary impact areas of each driver or barrier. Therefore, directly affected stakeholders are those, whose primary activities or responsibilities are immediately impacted by the barrier or driver.

4.4.1. Technological Challenges and Drivers to MP Adoption

The main technological challenges in MP adoption that research has so far identified revolve around the topic of data governance, focusing on the need for clear decision rights and reliable data management in multi-stakeholder settings. Van Capevelleen et. al. identified four sub challenges here, first being quality data generation and maintenance (1), which are a complex problem to solve, given the diversity in approaches from existing lifecycle registrations to advanced IoT applications (Ganter & Lützkendorf, 2019; Munaro et al., 2019; Munaro & Tavares, 2021). The second identified challenge is the lack of standardized data exchange (2), which complicates the linkage and sharing of data across stakeholders, hindered by diverse data formats and guidelines that vary by region and material-specific requirements (Debacker et al., 2016; Ganter & Lützkendorf, 2019). Other critical challenges are issues of ownership and confidentiality (3,4), when it comes to the data input to the MP. Data ownership is ambiguous in supply chains, with data seen as a valuable asset holding intellectual property, necessitating systems that manage data exchanges and ownership transfers effectively. Confidentiality concerns arise from the competitive nature of businesses and their reluctance to share proprietary information (Hermann et al., 2016). Another fundamental challenge is data integrity and accuracy (5), with auditing systems and blockchain suggested as solutions to guarantee data quality and trustworthiness (Merrild et al., 2016; Rudolphi, 2018) . These challenges underscore the need for robust technological frameworks to effectively implement and manage passports in circular economies.

Technological Barriers	**Primarily Affected Stakeholders**
(1) Quality data generation and maintenance	A1-A12
(2) Standardized data exchange (Interoperability)	A1-A12
(3) Data ownership	A1-A12
(4) Data confidentiality	A1-A12
(5) Data integrity and accuracy	A1-A12

Table 5: Technological challenges to MP adoption

The main technological drivers for MP adoption highlight several innovative advancements and methodologies that collectively enable the development of the multi-layered content model, as described in Section 4.3.1.. An important driver is the development and industry-wide acceptance of BIM (1), which enables a design operations for deconstruction, addressing the need to share information about the potential for reuse of materials during all building life cycles (Ganter & Lützkendorf, 2019; Heisel & Rau-Oberhuber, 2020; Munaro & Tavares, 2021). Research also suggests that Internet of Things IoT implementations (2) play a crucial role in increasing data quality by automating data collection, which reduces efforts and provides quicker and cheaper data than onsite audits (Barni et al., 2018; Merrild et al., 2016). Also, modern digital integration platforms (3) have emerged as complex and innovative drivers of MP adoption, transforming how the construction sector manages and utilizes material data. These platforms combine several cutting-edge technologies and methodologies, which collectively enhance their capability and impact (*Concular*, 2023, *Madaster*, 2022). Research also emphasizes the use of blockchain technology to improve documentation and accessibility of information, facilitating the use of MPs (Ganter & Lützkendorf, 2019; Rudolphi, 2018). Furthermore, research suggests that embedded sensors in materials may be able to detect and communicate current passport status while being accessible in real-time (Merrild et al., 2016).

Technological Drivers	**Primarily Affected Stakeholders**
(1) Building Information Modeling (BIM)	A3 - A9
(2) Internet of Things implementations (IoT)	A2-A12
(3) Advanced Digital Integration Platforms	A3 - A10, A12
(4) Blockchain Technology	A2 - A12
(5) Incorporation of sensors in Materials	A2 - A12

Table 6: Technological Drivers to MP adoption

4.4.2. Economic Barriers and Drivers to MP Adoption

The economic challenges in MP adoption are significant and impact various stakeholders. One major challenge is the upfront capital expenditure required to create MPs (1), with benefits realized only in the long term by different stakeholders (Munaro et al., 2019). High operating costs (2), especially data registration, are not directly paid off by owners who benefit, posing issues for firms focused on short-term profitability (Böckel et al., 2021). There is insufficient demand for MPs due to several interrelated concerns (3). Privacy issues make data providers reluctant to share proprietary information, impacting data availability. Quality concerns arise from uncertainties about the reliability and performance of secondary materials. Perception issues, including negative views on reused materials, further hinder their acceptance. These factors are collectively the economic viability and widespread adoption of MPs (Bokkinga, 20182018; Munaro & Tavares, 2023).

Economic Barriers	**Primarily affected stakeholders**
(1) Upfront capital Expenditure	A3, A4, A6, A8
(2) High operating costs of data registration	A3, A4, A6, A8
(3) Insufficient Customer Demand	A1 - A12

Table 7: Economic Barriers to MP adoption

The economic drivers for MP adoption are varied and offer substantial benefits to multiple stakeholders. The creation of a secondary material market (1) is a significant driver, providing redistributors of second-life materials with new business opportunities and supporting the CE (EPEA & SundaHus, 2019). Improved asset management (2) offers building owners better tracking and utilization of materials, leading to cost savings and increased asset value (Bouwend Bouwend Nederland, 2020). Time savings in maintenance (3) also benefit building owners by reducing the time and resources needed for upkeep (Bouwend Bouwend Nederland, 2020). Furthermore, the decrease of failure costs (4) ensures that building owners can mitigate risks and avoid costly repairs by utilizing detailed material data (Bouwend Bouwend Nederland, 2020). The efficiency of the construction process (5) is enhanced through MPs, as streamlined information flow and material tracking improve overall project management (Bouwend

Bouwend Nederland, 2020). MPs also create a market differential (6) for manufacturers and planners, enhancing the transparency and circular potential of their products (Luscuere, 2016). Protection against industrial counterfeiting, tampering, and misuse (7) is another crucial driver, safeguarding manufacturers and suppliers by ensuring the authenticity of materials (EPEA & SundaHus, 2019). The development of new business models and partnerships (8) fosters innovation and collaboration across the supply chain (Luscuere, 2016). Residual value of materials (9) provides building owners with economic benefits by maintaining the value of materials throughout their lifecycle (Bokkinga, 20182018; EPEA & SundaHus, 2019). Tax benefits through decreased environmental footprint (10) incentivize building owners and product manufacturers to adopt MPs by offering financial incentives for sustainable practices (Heinrich & Lang, 2019). Increased transparency and trust (11) build confidence among stakeholders, reducing risks and uncertainties (Munaro & Tavares, 2021; van Capelleveen et al., 2023). Regulatory compliance and incentives (12) help all stakeholders meet legal requirements and access financial incentives, promoting widespread adoption (Munaro & Tavares, 2021; van Capelleveen et al., 2023). Enhanced decision-making and planning (13) benefit building owners and project planners by providing detailed material data that inform strategic decisions (Munaro & Tavares, 2021; van Capelleveen et al., 2023). Market access and competitiveness (14) allow manufacturers and product suppliers to enter new markets with higher sustainability standards, offering a competitive edge (Munaro & Tavares, 2021; van Capelleveen et al., 2023). Lastly, the integration of CE principles (15) ensures that materials are reused, recycled, and retained within the economic cycle, leading to significant long-term cost savings and environmental benefits (Munaro & Tavares, 2021; van Capelleveen et al., 2023).

Economic Drivers	**Primarily Affected Stakeholders**
(1) Creation of Secondary Material Market	A2, A4, A8, A9, A10
(2) Improved asset management	A8
(3) Time saving in maintenance	A8
(4) Decrease of failure cost	A8
(5) Efficiency of construction process	A8

(6) Market differential	A2 - A11
(7) Protection against industrial counterfeiting, tampering and misuse	A3 & A4
(8) New business models and partnerships	A2 - A12
(9) Residual Value of Materials	A8
(10) Tax Benefits through decreased environmental footprint	A3, A4, A6, A7, A8
(11) Tax incentives due to Regulatory Compliance	A1 - A12
(12) Enhanced Decision-Making and Planning	A2 - A8

Table 8: Economic Drivers to MP adoption

4.4.3. Political Barriers and Drivers to MP Adoption

The political barriers to MP adoption in the construction industry are numerous and interconnected, creating a complex landscape that hinders implementation. A fundamental challenge is the lack of regulatory frameworks (1) and the absence of laws specifying MP requirements and use (2), which creates uncertainty and inconsistency across the sector (Böckel et al., 2021; Calisto Friant et al., 2021)

Inadequate stimulation of CE demand (4) further impedes adoption, as the economic incentives are not yet fully aligned with MP implementation (Böckel et al., 2021; Munaro et al., 2019). Limited government participation in passport design (3) and conflicting environmental policies (7) create additional obstacles, as they lead to inconsistent approaches and potentially contradictory requirements (Bouwend Nederland, 2020; Debacker et al., 2016). The lack of legal right to repair (5) and compliance issues with CE-based materials (6) further complicate the adoption of circular practices essential for MP success (Böckel et al., 2021). The absence of legal warranty and quality assurance for CE-based products (8) raises concerns about liability and performance, potentially discouraging the use of reused or recycled materials (Böckel et al., 2021).

Political Barriers	**Primarily Affected Stakeholders**
(1) Lack of regulatory frameworks	A1-10, A12
(2) Absence of laws specifying passport requirements and use	A2-A8, A10, A12

(3) Limited government participation in passport design	A12
(4) Insufficient stimulation of CE demand	A2-A4, A8-A10
(5) Lack of legal right to repair for firms and consumers	A4, A8
(6) Compliance issues with CE-based materials	A2-A4, A6-A7, A9 - A12
(7) Conflicting environmental policies	A2-A7, A12
(8) Absence of legal warranty and quality assurance for CE-based products	A2-A4, A8, A10

Table 9: Political Barriers to MP adoption

The political drivers for MP adoption in the construction industry are significant and interconnected. A fundamental driver is the upcoming EU law specifying MP requirements and use through the Digital Product Passport (DPP) (1), which is expected to become operational in 2027/28. This creates a clear regulatory framework and consistency across the sector, addressing previous uncertainties (*Digital Product Passport*, 2023). EU initiatives like BAMB (Buildings as Material Banks) and DBL (Digital Building Logbook) (2) further stimulate MP adoption by providing structured approaches and implementation orientation (Debacker & Manshoven, 2020; Gómez-Gil et al., 2023). At the national level, German initiatives to create regulatory frameworks specifically for MPs, such as the BBSR Gebäuderessourcenpass (3), demonstrate government participation in passport design and implementation (*BBSR Gebäuseressourcenpass*, 2024). This national approach complements EU-wide efforts and helps tailor MP requirements to the specific needs and conditions of the German construction sector.

Political Drivers	**Directly Affected stakeholders**
(1) Mandatory EU laws (a) EU Waste Framework Directive (b) Ecodesign for Sustainable Products Regulation (ESPR) - Digital Product Passport (DPP)	A1, A2, A3, A4, A9, A10, A12
(2) EU and German Policy Frameworks (a) CE Action Plan (EU level) (b) German Resource Efficiency Programme (ProgRess)	A1, A2, A3, A4, A6, A7, A8, A10, A12
(3) EU and German Guidelines and Strategies (a) Sustainable Building Strategy (Nachhaltiges Bauen) (National level)	A3, A4, A5, A6, A7, A8, A10, A12

(b) European Green Deal (EU level) (c) Cradle to Cradle Construction Initiative (National level)	
(4) Research Support (a) Various National and EU research programmes (b) BAMB (Buildings as Material Banks) (EU level) (c) Digital Building Logbook (DBL) (EU level)	A2-A10, 12

Table 10: Political Drivers to MP adoption

4.4.4. Socio-Temporal Drivers and Challenges to MP Adoption

The socio-temporal challenges to MP adoption in the construction industry are numerous and interconnected, creating a complex landscape that still hinders implementation. A fundamental challenge is the lack of trust between firms hindering information exchange (1), which creates barriers to the collaborative approach necessary for effective MP use (Böckel et al., 2021; Munaro & Tavares, 2021). This is exacerbated by a reluctance to share certain information due to business competition (2), further impeding the free flow of data crucial for comprehensive MPs (Böckel et al., 2021). The time required for widespread adoption and integration into existing processes (3) presents another significant hurdle, as the construction industry often resists rapid changes (Sepasgozar et al., 2020). This is closely linked to the adaption of operations to new circular practices (4), which requires overcoming long-established linear economy mindsets (Bouwend Nederland, 2020). Limited experiences and success stories to drive adoption (5) further complicate the landscape, as the lack of proven models can deter risk-averse stakeholders from embracing MPs (Sepasgozar et al., 2020). This challenge is compounded by the misalignment between short-term business goals and long-term sustainability benefits (6), which can discourage companies from investing in MP implementation (Böckel et al., 2021). These challenges affect all stakeholders (A1-A12) in the construction value chain to varying degrees, with manufacturers, architects, contractors, and suppliers (A3-A7) particularly impacted by issues of trust, competition, and business goal alignment.

Socio-Temporal Barriers	**Affected stakeholders**
(1) Lack of trust between firms hindering information exchange	A3, A4, A5, A6, A7
(2) Reluctance to share certain information due to business competition	A3, A4, A5, A6, A7
(3) Time required for widespread adoption and integration into existing processes	A1-A12
(4) Adapting operations to new circular practices	A1-A12

(5) Limited experiences and success stories to drive adoption	A1-A12
(6) Misalignment between short-term business goals and long-term sustainability benefits	A3, A4, A5, A6, A7

Table 11: Socio-Temporal Barriers to MP adoption

The socio-temporal drivers for MP adoption in the construction industry are multifaceted and interconnected, creating a dynamic landscape that promotes implementation. A fundamental driver is the increasing awareness of CE concepts (1), which is fostering a more receptive environment for MPs across all stakeholders (Bouwend Nederland, 2020). This is complemented by a growing recognition of the value of material and product information (2), which underscores the importance of MPs in facilitating informed decision-making throughout the building lifecycle (Hansen et al., 2020). The shift towards more sustainable and responsible resource management (3) is another crucial driver, aligning MPs with broader sustainability goals in the construction sector (Debacker and Manshoven, 2016). This is further reinforced by evolving consumer preferences for sustainable products and practices (4), particularly affecting owners, users, and retailers (Malmgren & Mötsch Larsson, 2020). Technological advancements enabling better data collection and management (5) are also playing a pivotal role in making MPs more feasible and effective (Merrild et al., 2016). These advancements facilitate the creation, maintenance, and utilization of MPs across all stakeholders in the construction value chain. These drivers collectively affect all stakeholders (A1-A12) in the construction industry, from raw material suppliers to end-users and recyclers, creating a favorable environment for the adoption and implementation of MPs.

Socio-Temporal Drivers	**Affected stakeholders**
(1) Increasing awareness of CE concepts	A1-A12
(2) Growing recognition of the value of material and product information	A1-A12
(3) Shift towards more sustainable and responsible resource management	A1-A12
(4) Evolving consumer preferences for sustainable products and practices	A1, A2, A8
(5) Technological advancements enabling better data collection	A1-A12

and management	

Table 12: Socio-Temporal Drivers to MP adoption

4.4.5. Quantitative summary of MP adoption factors

To systematically compare the drivers and barriers affecting the adoption of MPs across all relevant stakeholder groups, this Section 4.4.5. applies the PEST framework, categorizing influencing factors as Political, Economic, Social, or Technological. For each CC actor, the analysis draws on the known factors identified in the literature analysis and counts them within each PEST category. In addition to this category-specific view, the total number of drivers and barriers per stakeholder is also presented to highlight the relative weight of influencing conditions across roles in the material life-cycle. Finally a quantitative comparison is presented in Section 4.4.8.. Table 13 starts with the quantitative collection of barriers to MP adoption for each stakeholder group, disaggregated by PEST category. For a detailed overview of the specific adoption factors and their categorization within the respective PEST dimensions, refer to Appendix A1.

Life-cycle stage	CC actor	Amount Technological Barriers	Amount Economical Barriers	Amount Political Barriers	Amount Socio-Temporal Barriers	Total Amount Barriers
(1) Raw material extraction	**A1: Raw material supplier**	4	1	1	3	**9**
	A2: Recycler / Urban Miner	4	1	4	3	**12**
(2) Manufacturing/ Design	**A3: Component designers**	4	3	6	6	**19**
	A4: Component manufacturers	4	3	7	6	**20**

(3) Planning/ Construction	**A5&A6: Planners (Architects/ Engineers)**	4	3	4	6	**17**
	A7: Construction company	4	1	4	6	**15**
(4) Operation/ Maintenance	**A8: Building Owner**	4	3	5	3	**15**
(5) End of Life	**A9: Dismantling firm**	4	1	3	3	**11**
	A10: Redistributors of second-life materials	4	1	4	3	**12**
(6) Logistics / Reverse Logistics	**A11: Logistics Firm**	4	1	1	3	**9**
(7) Material Information Exchange	**A12: Material Passport Operator**	5	1	5	3	**14**

Table 13: Quantitative collection of all stakeholder perspectives on barriers to MP Adoption

Table 14 provides the equivalent quantitative overview of drivers supporting MP adoption. Again, each known driver is allocated to a stakeholder group and categorized by PEST dimension. Total counts allow for a clearer picture of which stakeholders currently operate under more favorable conditions and where the most enabling factors are concentrated on a purely quantitative level.

Life-cycle stage	CC actor	Amount Economical Drivers	Amount Political Drivers	Amount Socio-Temporal Drivers	Sub - Amount Drivers	Total Amount Drivers
(1) Raw material extraction	A1: Raw material supplier	1	1	2	5	9
	A2: Recycler / Urban Miner	3	5	3	5	16
(2) Manufacturing/ Design	A3: Component designers	5	5	4	4	18
	A4: Component manufacturers	5	7	4	4	20
(3) Planning/ Construction	A5&A6: Planners (Architects/Engineers)	5	5	3	4	17
	A7: Construction company	5	5	3	4	17
(4) Operation/ Maintenance	A8: Building Owner	5	4	3	5	17
(5) End of Life	A9: Dismantling firm	5	5	2	4	16
	A10: Redistributors of second-life materials	5	4	4	4	17

(6) Logistics / Reverse Logistics	**A11: Logistics Firm**	3	3	0	4	**10**
(7) Material Informatio n Exchange	**A12: Material Passport Operator**	4	1	4	4	**13**

Table 14: Quantitative collection of all stakeholder perspectives on drivers to MP Adoption

4.4.8. Summary

The adoption of MPs in the construction industry presents a complex interplay of drivers and barriers across various stakeholders. A critical insight from this analysis is the misalignment of interests and responsibilities among different actors in the value chain (see Figure 8). While some stakeholders have more drivers than barriers of MP adoption, thus being more incentivised for implementation of MPs (A2: Recyclers/Urban Miners, A9: Dismantling Firms, A10: Redistributors of second life materials), others have overall more barriers and less or an equal amount of drivers for MP implementation (A3: Component designers, A4: Component

Manufacturers, A6: Planners, A12: MP Operators)

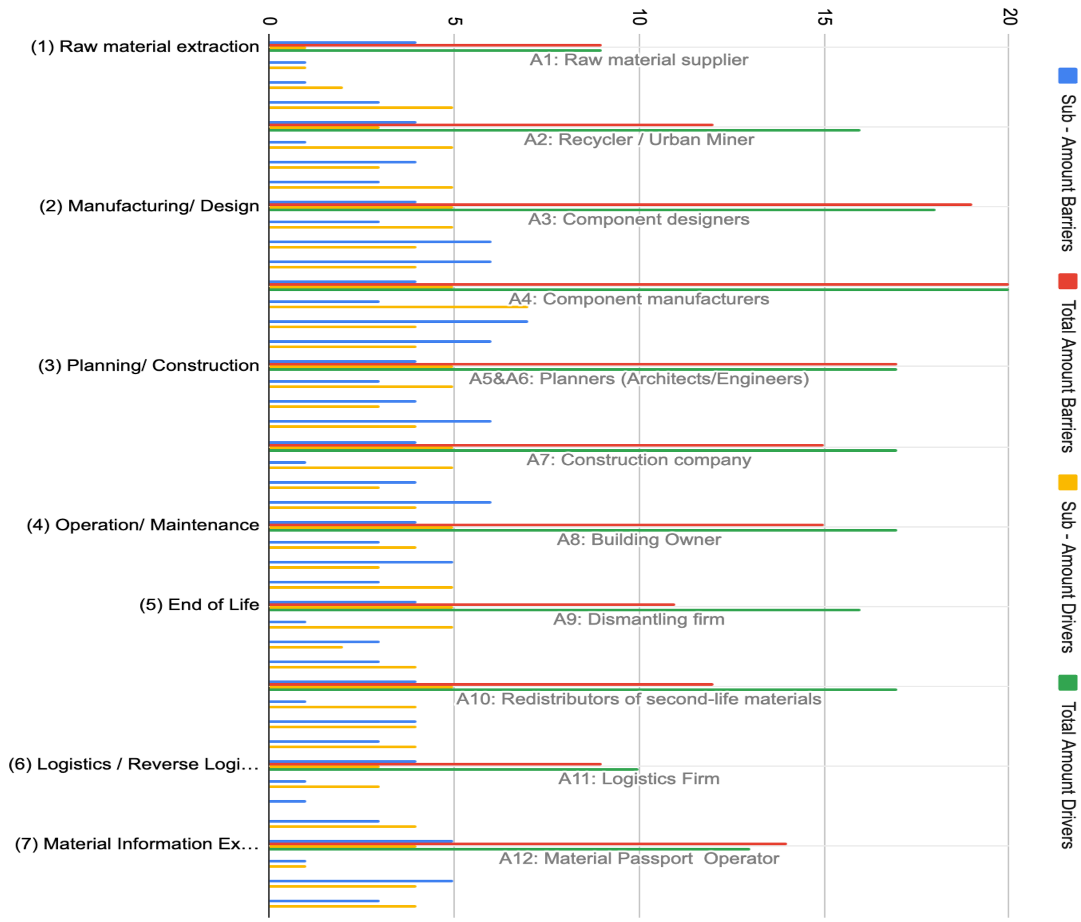

Figure 8: CC Stakeholders and their MP adoption drivers and barriers compared

Furthermore, the potential for adversarial barrier and driver relationships cannot be overlooked, potentially disadvantaging certain actors such as recyclers. Given that many of the identified drivers and barriers remain theoretical assumptions, it is imperative to conduct empirical research to examine stakeholder behavior in real-world scenarios. Such studies would provide valuable insights into the practical challenges of MP adoption and help in developing strategies to address the misalignment of interests.

4.5. Summary of Literature Review

The reviewed literature demonstrated insufficient efforts in the implementation of the MP in the construction sector. Despite being an efficient tool in the optimization of projects and facilitating the reuse of materials, it is still not widespread in the sector. There is a lack of research and awareness on the opportunities that the MP will provide to stakeholders in the construction sector, as well as, the challenges to adopting this tool. It is not yet clear what data and essential information the MP must provide during the life cycle of the building, supporting the BIM, ITs and new business model development. Therefore, exploring these issues is essential for the incorporation of circular principles in the construction sector. (Munaro and Tavares, 2021)

As the pressure on the construction industry for more sustainable practices has drastically increased in recent years, MPs have gained traction in its development as a commercial product (*Concular*, 2023, *Madaster*, 2022). Despite the progress made in formalizing the concept of MPs and identifying potential research gaps, there remains a significant gap in understanding the practical implementation and commercial adoption of this tool (Benachio et al., 2020; Munaro & Tavares, 2021; van Capelleveen et al., 2023). Therefore, further investigation is required to gain insights into the adoption of MPs, especially more research on understanding the prerequisites and barriers existing in the process of a MP conceptualisation from the academia, given the low number of articles in this area (Benachio et al., 2020).

Despite the theoretically identified potential of the MP concept, a significant gap exists in the understanding of the practical adoption barriers and challenges, requirements and effectiveness of MPs in promoting CE practices within the industry (Benachio et al., 2020; Honic et al., 2021; Munaro & Tavares, 2021; van Capelleveen et al., 2023). Research of MP adoption, particularly in the commercial context, is very limited. In a recent literature review by Benachio et al. (Benachio et al., 2020) only 3 studies were identified, which developed and explored the implementation of MPs, and only within a science - project - context. This research aims to delve into this knowledge gap, exploring the prerequisites and challenges through the examination of the adoption and successful implementation of commercially used MPs in the construction industry. Without a comprehensive understanding of the experiences of early adopters of MPs, it becomes challenging to verify the assumptions of current research models of MPs, thus inhibiting their potential evolution and optimization.

5. Research Methodology

Chapter 5 outlines the methodological approach used to investigate the adoption of MPs among stakeholders in the CC industry. It begins by presenting the overall research design, which employs an adapted Delphi method within a mixed methods framework to capture both qualitative insights and quantitative measurements of stakeholder perspectives. It then details the study site selection, participant sampling strategy, and data collection procedures used to gather comprehensive information from key stakeholders across different stages of the construction lifecycle. Finally, it explains the analytical framework that will be applied to interpret the findings, combining thematic analysis of interview data with statistical analysis of Likert-scale responses. This methodological approach is designed to provide a holistic understanding of the drivers, barriers, and prerequisites for MP adoption, contributing to both theoretical knowledge and practical implementation strategies in the field of CC.

5.1. Research Design

5.1.1. Adapted Delphi Method

This study employs an adapted Delphi method to achieve a more precise estimation of the key factors influencing MP adoption through an iterative questioning process. The Delphi method is a structured communication technique that involves multiple rounds of questioning, allowing participants to reconsider their responses in light of the group's feedback (Dalkey & Helmer, 1963). By conducting multiple iterations, the Delphi method helps to refine the data and converge toward a common understanding among stakeholders. Okoli and Pawlowski (Okoli & Pawlowski, 2004) highlight the effectiveness of the Delphi method in information systems research for harnessing expert knowledge and achieving reliable consensus.

The adjusted Delphi approach proposed in this study includes two primary rounds and is illustrated in Figure 9:

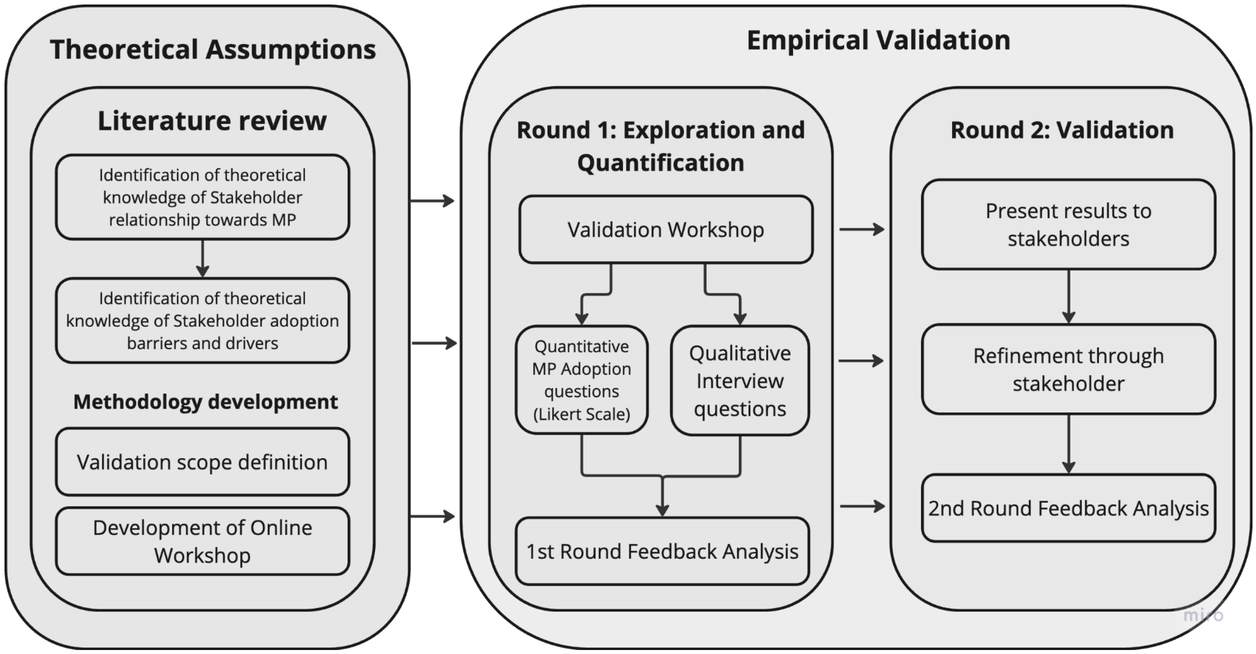

Figure 9: Adjusted delphi method (self made)

First Round: Exploration and Quantification - In the first round, stakeholders participate in both qualitative (semi-structured interviews) and quantitative (Likert scale) activities. This mixed approach allows for identifying both the significance of known drivers and barriers, as well as uncovering new factors through open-ended exploration. The mixed methods approach is aligned with similar methodologies used in circularity research, where stakeholder feedback and model validation are achieved through structured iterations.

Second Round: Validation - The second round involves summarizing the adoption situation of each stakeholder and presenting it back to them for validation. This iterative approach allows participants to reflect on their initial responses, providing an opportunity for them to either affirm or refine their viewpoints. The iterative nature of the Delphi method is well-suited for this study since the objective is not necessarily to achieve consensus among all participants but rather to validate and expand upon individual insights. This approach effectively captures the varied barriers and drivers in the adoption process.

5.1.2. Mixed Methods Approach

Within the Delphi framework, this study adopts a mixed methods research approach, combining qualitative and quantitative methods to investigate the adoption of MPs among stakeholders in the CC industry. The combination is justified by the complex nature of the research questions, which require both in-depth insights into stakeholders' perspectives and measurable data on the significance of various drivers and barriers to MP adoption (Akotia et al., 2023). According to Creswell and Plano Clark (Creswell & Clark, 2011), mixed methods research enables researchers to draw on the strengths of both qualitative and quantitative approaches, providing a more comprehensive understanding of research problems than either approach alone.

The mixed methods approach in this study involves conducting online workshops with stakeholders, where participants engage in:

1. **Qualitative Component**: Semi-structured interviews to gather rich, textual data on stakeholder perspectives. Qualitative methods, as noted by Bryman (2017), are particularly effective for capturing nuanced, textual data and facilitating an in-depth exploration of open-ended questions. This method allows for flexibility in exploring emerging themes while ensuring coverage of predetermined topics related to MP adoption.
2. **Quantitative Component**: Likert-scale surveys to quantify the importance of identified drivers and barriers. The use of the Likert scale is particularly suitable for capturing stakeholders' attitudes and perceptions in a structured manner. Likert scales are effective in measuring the importance of various factors by allowing respondents to express their level of agreement or disagreement, thus facilitating the quantification of subjective opinions (Joshi et al. 2015).

As noted by Greene et al. (Greene et al., 1989), integrating qualitative and quantitative data can lead to greater validity through triangulation and provide complementary insights that enhance the overall findings. This integration occurs at both data collection and analysis stages, creating a comprehensive understanding of MP adoption factors.

5.2. Study Site and Participant Selection

5.2.1. Study Site Selection

Germany has been chosen as the study site due to its prominent role in the European construction sector and its significant contributions to sustainable building practices globally (Pfnür & Wagner, 2020). The nation's leadership in integrating sustainability into construction offers a compelling context for investigating MP adoption (Debacker & Manshoven, 2020). Furthermore, Germany's regulatory environment and industry initiatives in CE principles provide a rich backdrop for this research.

5.2.2. Participant Sampling Strategy

The study employs a purposive sampling method, specifically using critical case sampling as demonstrated by Schraven et al. (Schraven et al., 2019) in their study of the Dutch stony materials supply chain. The approach targets individuals who can provide detailed insights into the adoption and use of MPs across different lifecycle stages in construction projects. The sampling process begins by consulting branch organizations, a method validated by Schraven et al. (Schraven et al., 2019) as effective for identifying companies actively engaged in circular initiatives. This ensures that selected participants are knowledgeable and can contribute meaningfully to understanding MP adoption barriers and drivers.

Interview partners are selected based on the lifecycle stages of the CC Economy (Section 4.3.4; see Figure 7), with at least one stakeholder interviewed per stage. This approach aligns with Schraven et al.'s findings that different stages of the construction chain exhibit varying levels of influence in circular transitions. An exception is made for the Raw Material Extraction phase, due to its relatively low circularity impact and minimal influence on circular transitions, as observed by Schraven et al. (Schraven et al., 2019).

To ensure data quality, companies must demonstrate active involvement in circular initiatives and possess substantial knowledge of MPs, following Schraven et al.'s observation that valuable insights come from those deeply engaged in circular transitions. This approach ensures high-quality data collection while addressing both theoretical and practical needs in CC research.

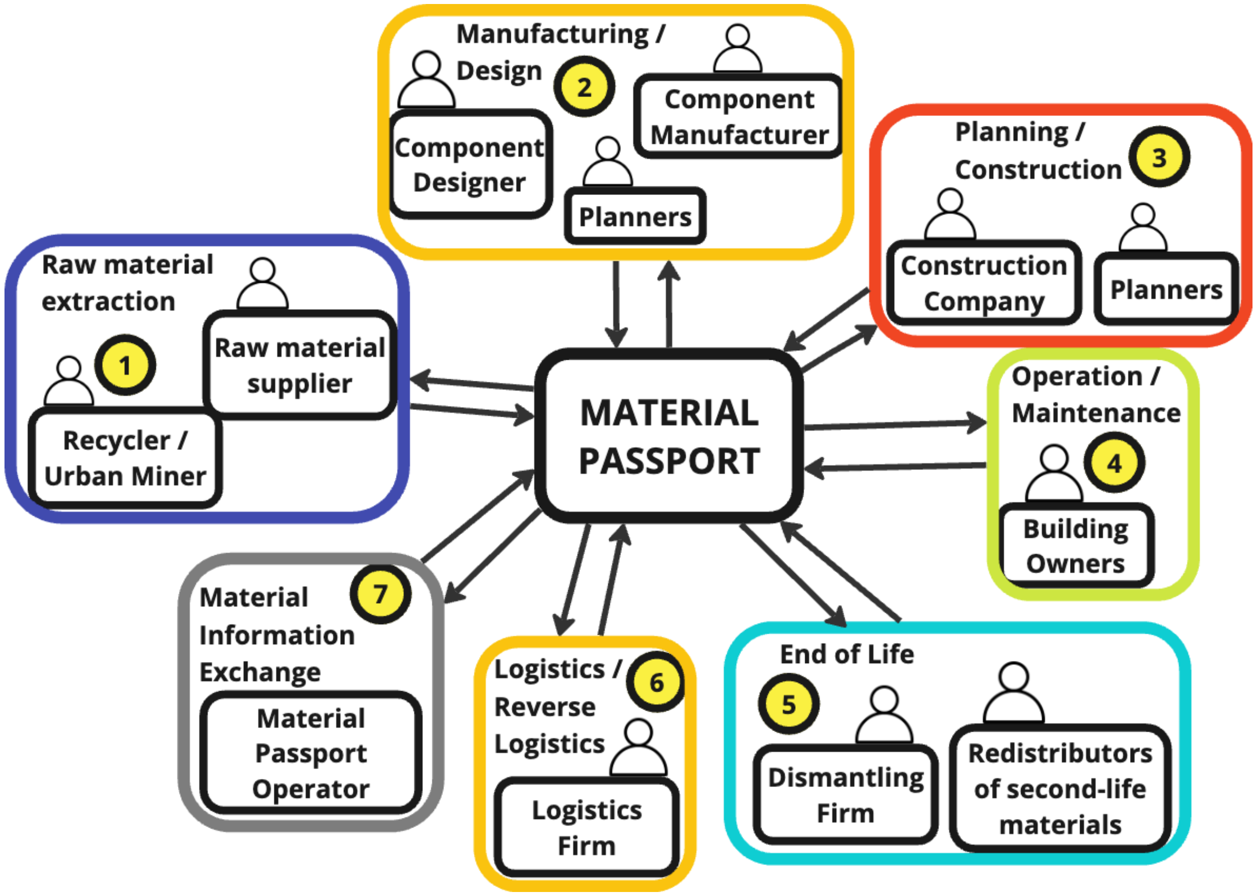

Figure 7: Visualization of the Stakeholder relationships towards MPs

5.2.3. Interview Partners and Their Roles

Section 5.2.3. introduces the various interview partners' roles in the CC industry, along with their theoretically assumed relationships to MPs and potential adoption barriers and drivers. These theoretical assumptions serve as the foundation for developing standardized interview questions tailored to each stakeholder group.

(1) Raw material provider

A1: Raw material supplier

This stakeholders role in the CC supply chain lies in supplying sustainably sourced and certified raw materials that are appropriate for circular use in construction. Ensures that the materials can be reused, recycled, or safely returned to nature at the end of their lifecycle.

Verify theoretical assumptions on relationship towards MP (Qualitative method)
This stakeholder is theorized to utilize MP data to improve their sourcing strategies based on feedback from downstream users about material performance and sustainability metrics. A semi-structured interview will be conducted to verify these assumptions in practice.

Verify theoretical assumptions towards MP adoption (Quantitative method)
A likert-scale survey will be conducted to verify and weigh the assumptions identified in the PEST analysis of the barriers and drivers of Raw Material suppliers towards MP adoption (Section 4.4.5 and 4.4.6.).

A2: Recycler / Urban Miner
Focuses on reclaiming valuable materials from waste or decommissioned structures, converting what might otherwise be debris into usable raw materials, hence supporting the recycling loop and reducing the need for virgin materials.

Verify theoretical assumptions on relationship towards MP (Qualitative method)
This stakeholder is theorized to use MP data for transparent data elements information about object/object components to identify circular potentials and enhance sorting efficiency. He also is theorized to use of MP for resource recovery planning as MP provides data on quantities of material that can be regained at a certain time. A semi-structured interview will be conducted to verify these assumptions in practice.

Verify theoretical assumptions towards MP adoption (Quantitative method)
A likert-scale survey will be conducted to verify and weigh the assumptions identified in the PEST analysis of the barriers and drivers of Raw Material suppliers towards MP adoption (Section 4.4.5. and 4.4.6.).

(2) Manufacturing/ Design

A3: Component Designers

Designs building components that are durable, modular, energy and resource - efficient and suitable for disassembly and reuse. Ensures that components can be easily integrated into different structures and adapted to various uses over time.

Verify theoretical assumptions on relationship towards MP

This stakeholder is theorized to utilize MP data to inform CE-based design decisions, ensuring compatibility with existing materials and systems, and to integrate lifecycle impact information into eco-friendly design practices. A semi-structured interview will be conducted to verify these assumptions in practice.

Verify theoretical assumptions towards MP adoption (Quantitative method)

A likert-scale survey will be conducted to verify and weigh the assumptions identified in the PEST analysis of the barriers and drivers of Raw Material suppliers towards MP adoption (Section 4.4.5. and 4.4.6.).

A4: Component manufacturers

Produces sustainable and high-quality construction components based on circular principles. This includes the repair, refurbishing, remanufacturing or repurposing of construction materials and ensuring that the components themselves are recyclable at the end of their use.

Verify theoretical assumptions on relationship towards MP (Qualitative method)

This stakeholder is theorized to leverage MP data for CE-based manufacturing decisions, verifying sustainability credentials and origin of raw materials, and ensuring compliance with environmental and building standards. A semi-structured interview will be conducted to verify these assumptions in practice.

Verify theoretical assumptions towards MP adoption (Quantitative method)

A likert-scale survey will be conducted to verify and weigh the assumptions identified in the PEST analysis of the barriers and drivers of Raw Material suppliers towards MP adoption (Section 4.4.5. and 4.4.6.).

(3) Planning/ Construction

A6: Planners (Architects/Engineers)

Develops building designs and plans that incorporate CC principles, including the planning with available second-life materials. This includes optimizing the use of resources, designing for longevity, adaptability, and future disassembly. Gives life cycle feedback of objects (e.g. material choices) to make better product design choices for circular goals.

Verify theoretical assumptions on relationship towards MP (Qualitative method)

This stakeholder is theorized to employ MP data to assess second-life materials for building planning, utilize decision-making support tools for deconstructability and efficient resource use, and plan for low CO2 emissions and future reuse.
A semi-structured interview will be conducted to verify these assumptions in practice.

Verify theoretical assumptions towards MP adoption (Quantitative method)

A likert-scale survey will be conducted to verify and weigh the assumptions identified in the PEST analysis of the barriers and drivers of Raw Material suppliers towards MP adoption (Section 4.4.5. and 4.4.6.).

A7: Construction company

Implements construction projects based on sustainable practices. Ensures that construction processes minimize waste and environmental impact, and that materials are handled in ways that preserve their value for recycling or reuse.

Verify theoretical assumptions on relationship towards MP (Qualitative method)

This stakeholder is theorized to use MP data elements for assembly and installation processes, enhancing material traceability and management on construction sites.
A semi-structured interview will be conducted to verify these assumptions in practice.

Verify theoretical assumptions towards MP adoption (Quantitative method)

A likert-scale survey will be conducted to verify and weigh the assumptions identified in the PEST analysis of the barriers and drivers of Raw Material suppliers towards MP adoption (Section 4.4.5. And 4.4.6.).

(4) Operation/ Maintenance

A8: Building Owner

Manages properties with a focus on sustainability throughout the building's lifecycle. Invests in maintenance and upgrades that prolong the life of the building and its components, supporting CE principles.

Verify theoretical assumptions on relationship towards MP (Qualitative method)

This stakeholder is theorized to utilize MP interactive decision support tools for efficient building management during the use phase, and to plan for eventual material recovery and building deconstruction. A semi-structured interview will be conducted to verify these assumptions in practice.

Verify theoretical assumptions towards MP adoption (Quantitative method)

A likert-scale survey will be conducted to verify and weigh the assumptions identified in the PEST analysis of the barriers and drivers of Raw Material suppliers towards MP adoption (Section 4.4.5. and 4.4.6.).

(5) End of Life

A9: Dismantling firm

Responsible for the careful deconstruction of buildings at the end of their life, aiming to maximize the recovery of materials and components for reuse or recycling, thus closing the loop in the CC process.

Verify theoretical assumptions on relationship towards MP (Qualitative method)
This stakeholder is theorized to employ MP data to plan and execute building deconstruction in a way that maximizes material recovery and reuse potential. A semi-structured interview will be conducted to verify these assumptions in practice.

Verify theoretical assumptions towards MP adoption (Quantitative method)
A likert-scale survey will be conducted to verify and weigh the assumptions identified in the PEST analysis of the barriers and drivers of Raw Material suppliers towards MP adoption (Section 4.4.5. and 4.4.6.).

A10: Redistributors of second-life materials
Manages the collection, sorting, and redistribution of used materials that are still in good condition. Provides a marketplace for second-life materials, facilitating their reintroduction into the construction cycle.

Verify theoretical assumptions on relationship towards MP (Qualitative method)
This stakeholder is theorized to use MP data to evaluate second-life products, handle procurement flows more efficiently, and provide detailed material history and quality information to potential buyers. A semi-structured interview will be conducted to verify these assumptions in practice.

Verify theoretical assumptions towards MP adoption (Quantitative method)
A likert-scale survey will be conducted to verify and weigh the assumptions identified in the PEST analysis of the barriers and drivers of Raw Material suppliers towards MP adoption (Section 4.4.5. And 4.4.6.).

(7) Material Information Exchange

A12: Material Passport Operator

Specializes in creating, managing, and maintaining digital MPs for construction materials and products. Responsible for collecting, organizing, and storing detailed information about materials throughout their lifecycle.

Verify theoretical assumptions on relationship towards MP (Qualitative method)

This stakeholder is theorized to utilize feedback from MP users to continuously refine and enhance the functionality, accessibility, and overall value of the MPs.
A semi-structured interview will be conducted to verify these assumptions in practice.

Verify theoretical assumptions towards MP adoption (Quantitative method)

A likert-scale survey will be conducted to verify and weigh the assumptions identified in the PEST analysis of the barriers and drivers of Raw Material suppliers towards MP adoption (Section 4.4.5. And 4.4.6.).

5.3. Data Collection and Analysis

5.3.1. Data Collection Methods

Data collection will be conducted through a combination of semi-structured interviews and Likert-scale surveys, as part of the mixed methods approach outlined in Section 5.1. This approach allows for the collection of both qualitative and quantitative data, providing a comprehensive understanding of stakeholders' perceptions and experiences regarding MP adoption.

The interview protocol will be designed around the PEST (Political, Economic, Social, Technological) framework, ensuring comprehensive coverage of the various factors influencing MP adoption. Key themes to be explored include:

- Understanding the utility of MPs towards their operation
- Current practices related to material tracking and CE principles

- Perceived drivers and barriers to MP adoption in all four PEST dimensions

Interviews will be conducted in person where possible, or via video conferencing when necessary. Each interview is expected to last approximately 60-90 minutes.

The Likert-scale surveys will be used to quantify stakeholders' attitudes and perceptions, allowing respondents to rate the importance of various drivers and barriers to MP adoption. This quantitative component provides a structured means to identify patterns and compare the significance of different factors across stakeholders, thus complementing the qualitative insights gathered from interviews.

5.3.2. Data Analysis Approach

For data analysis, a combination of thematic analysis and quantitative analysis will be utilized. Thematic analysis, as described by Guest et al. (Guest, MacQueen, and Namey 2011), is a flexible tool for identifying and analyzing patterns (themes) within qualitative data. It is particularly suitable for this study's aim to uncover the multifaceted factors influencing MP adoption. The qualitative data gathered through semi-structured interviews will be analyzed using thematic analysis, allowing for the identification of recurring themes and the exploration of complex stakeholder perspectives.

The PEST framework will guide both data collection and analysis. During thematic analysis, identified themes will be categorized according to the PEST dimensions, providing a structured understanding of how political, economic, social, and technological factors influence MP adoption. This approach will facilitate the development of a comprehensive model of MP adoption in the construction industry.

In addition to thematic analysis, the quantitative data gathered from the Likert-scale surveys will be analyzed statistically. Descriptive statistics will be used to summarize the responses, providing an overview of stakeholder attitudes toward drivers and barriers to MP adoption. The use of Likert-scale ratings enables a comparative analysis of the significance of different factors, thus helping to validate the qualitative insights obtained from the interviews.

By combining qualitative thematic analysis with quantitative analysis of Likert-scale data, this study ensures the reliability and validity of the findings. Integrating these two methods allows for triangulation, which enhances the overall robustness of the research by cross-validating the results from multiple data sources (Greene et al., 1989). This mixed-method approach provides a holistic view of the factors influencing MP adoption, enabling both depth and breadth of analysis.

6. Results

Chapter 6 builds on the foundation laid by the literature review, which explored theoretical drivers, barriers, and stakeholder perspectives on MP adoption. The analysis aims to validate and expand these insights through the empirical data collected via interviews, offering a deeper understanding of the practical dynamics influencing MP adoption. By integrating findings from open interviews with diverse MP stakeholders across the material lifecycle into a structured quantitative analysis based on the Political, Economic, Social, and Technological (PEST) framework (Blokdyk, 2018), this analysis aims to uncover additional adoption factors, stakeholder-specific perspectives, and broader systemic challenges.

This chapter unfolds as follows: Section 6.1. begins with a detailed examination qualitative analysis of open interview responses of each stakeholder group. This step focuses on identifying novel MP adoption factors, previously possibly unaddressed in the literature. The analysed insights will include both novel adoption factors, and broader stakeholder specific observations related to MP adoption, even if they do not directly qualify as adoption factors. These findings will then feed into the quantitative analysis in Section 6.2.. Here, a structured individual and collective analysis of the weighted MP adoption factors derived from the likert-scale questionnaire will be conducted, identifying and visualising so called “bottleneck”- and “facilitator” stakeholders. Finally, Section 6.3. will then combine these two results, providing a synthesis of the qualitative and quantitative analyses to identify the most critical adoption factors and stakeholder dynamics.

6.1. Qualitative Analysis: Novel adoption factors

Building on the theoretical foundation established in the literature review, this Section 6.1. presents a qualitative analysis of stakeholder insights across the material lifecycle to deepen our understanding of MP adoption dynamics. Through open interviews with key stakeholders, the analysis aims to uncover previously unidentified adoption factors and stakeholder-specific considerations that may have been overlooked in existing research. The insights gathered here will form the basis for the weighted factor evaluation presented in Section 6.2, creating a comprehensive framework for understanding the practical challenges and opportunities in MP implementation.

6.1.1. Novel stakeholder adoption factors

Stage 1: Raw Material Extraction

Position of the interviewee	Project Manager
Company	Urban Mining Company
Years of expertise	3
Market Region	Berlin / Brandenburg, GER
Company size	SME
Life-cycle stage	1. Raw Material Extraction
Interview date:	16.12.2024

Political/Legal

Bureaucratic Over - Complexity: Construction industry bureaucracy poses unique challenges, with the interviewee noting that *“the entire construction industry is over-bureaucratized”* (Interview 1, 2024, 00:22:41). Existing regulations developed for conventional construction methods don't easily transfer to circular practices.

Legal Precedent Requirements: The lack of legal precedents for reuse materials creates a significant barrier. *“As long as there hasn't been a precedent case, it's extremely difficult to interpret laws in a new way”* (Interview 1, 2024, 00:23:41). Interviewee 1 argues that this creates a situation where adoption is hindered by lack of precedents, but precedents require implementation.

Economic

Limited Availability of Cost-Effective Materials with Strong Performance: Interviewee 1 argues that the primary barrier is inadequate supply-side innovation rather than insufficient demand: *“The supply is not yet good enough to justify greater demand”* (Interview 1, 2024, 00:19:31). This suggests market development needs to prioritize on improving the availability of qualitative and circular materials over demand stimulation.

Technological

Process Innovation Gaps: While data collection and planning tools exist, practical implementation capabilities lag behind: *"We are further along with data and data management but the practical implementation is lacking"* (Interview 1, 2024, 00:11:32). This extends beyond technical capabilities to encompass the entire implementation process.

Stage 2: Manufacturing / Design

Position of the interviewee	Chief Executive Officer
Company	Circular Material Manufacturer
Years of expertise	8
Market Region	North Rhine-Westphalia, GER
Company size	SME
Life-cycle stage	2. Manufacturing / Design
Interview date:	02.12.2024

Political

Resource Security: The interview highlighted a political driver: the role of MPs in ensuring resource security as part of national and industrial strategies. The interviewee emphasized, *"Securing our own future resources… because we are basically dependent on numerous minerals and raw materials that we simply do not find in Europe"* (Interview 2, 2024, 00:44:44) highlighting the importance of securing access to critical materials in response to geopolitical uncertainties and supply chain vulnerabilities. This perspective positions MPs as tools not only for circularity but also for strategic material resilience (Interviewee, 2024).

Bureaucratic Over - Complexity: The interview also pointed to the challenge of regulatory overlap as a barrier to MP adoption. Manufacturers already face extensive compliance obligations, such as supply chain regulations and sustainability reporting. MPs are thus perceived as redundant, with the interviewee stating, "*The manufacturers say: "What do you want now? Supply chain laws already evaluate everything—now we need to fulfill the same requirements again?""* (Interview 2, 2024, 00:26:21) This contributes to what the interviewee described as a strong compliance fatigue in the industry. This underscores the need for policymakers to align MP requirements with existing regulations to avoid unnecessary duplication.

Economic

Circular Construction Financing / Asset Redefinition: A fundamental economic shift is proposed in how building components are valued. The interviewee articulates at 00:22:55 that *"in the circular economy, the building component becomes the asset. Today, the building itself is the asset; today, the building is what gets financed."*(Interview 2, 2024). This represents a paradigm shift in construction finance, suggesting that individual components could be financed over multiple use cycles rather than treating buildings as single assets.

Perception Gap Regarding Economic Utility: The interviewee questioned the economic impact of MPs, citing a perception gap regarding their utility. Manufacturers with established sustainability practices perceive MPs as offering limited added value, as the interviewee remarked, "Resource management is already there—MPs don't add much impact." This skepticism challenges the economic rationale for adoption and underscores the need for clearer communication of MPs' unique benefits, particularly in driving cost savings or market differentiation (Interviewee, 2024).

Technological

Open-Source Systems: The interview strongly advocates for open-source platforms as crucial to MP success. At 00:04:52, the interviewee emphasizes: "If I had one wish, then from my point of view, it should really be an open-source cloud." (translated from german). This is seen as essential for preventing monopolistic control and ensuring broad industry adoption.

Stage 3. Planning / Construction

Position of the interviewee	Chief Sustainability Officer

Company	Construction Company
Years of expertise	11
Market Region	Germany, Austria and Switzerland
Company size	Large enterprise
Life-cycle stage	3. Planning / Construction
Interview date:	06.12.2024

MPs are recognized in the literature as valuable tools for construction companies, supporting sustainability compliance and CC practices (van Capelleveen et al., 2023). They enhance material traceability and decision-making, while also enabling reuse and recycling opportunities. However, barriers like insufficient customer demand, regulatory gaps, and integration challenges hinder adoption (Honic et al., 2021). While these factors provide an important foundation, the interview with the Chief Sustainability Officer of a large sized, german construction company revealed several previously unidentified factors affecting MP adoption in the construction industry.

Political/Regulatory

Standardization Uncertainty: The interview highlighted a crucial gap in MP standardization: "in Germany that would be replaced by the new one... it will then be called digital resource passport for buildings... I hope this will be the standard then" (3. Interview, 2024, 00:32:51). This uncertainty around standards creates adoption hesitation.

Multi-Level Policy Implementation: A novel insight emerged regarding the hierarchy of regulatory implementation: "a lot has to come directly from the EU and then of course you can tighten the regulations according to member state... when it comes from the EU, there's no if and but" (3. Interview, 2024, 00:26:24).

Economic

Technical Interface Challenges: A critical economic barrier emerged regarding system integration: "*the interface between BIM and the material passport tools still doesn't work 100%*"

(3. Interview, 2024, 00:21:58). This technical limitation creates additional manual work costs: "manual effort, so some things have to be done manually, which is expensive" (3. Interview, 2024, 00:22:12).

<u>Socio-Cultural</u>

Educational System Integration: The interview revealed gaps in professional education: "*at some universities it's still not a mandatory subject to conduct an LCA or circular economy doesn't really come up in depth anywhere in any subject*" (3. Interview, 2024, 00:16:39). This lack of academic integration hinders widespread adoption knowledge.

Organizational Size Impact: A particularly novel finding relates to how company size influences MP adoption capabilities. The research reveals a distinct advantage for smaller, more agile organizations: "*in a startup that has set circular economy as a goal, it's easier to make quick changes than in a huge company that has been established for a long time, is relatively conventional, and has been building the same way for years*" (Interviewee, 2024, 00:30:31). This organizational dimension introduces a new perspective on adoption barriers, suggesting that organizational inertia in larger construction companies can significantly impede MP implementation.

Stage 4. Operation / Maintenance

Position of the interviewee	Sustainability Manager
Company	Residential Real Estate Developer
Years of expertise	7
Market Region	Berlin / Brandenburg, GER
Company size	Large enterprise
Life-cycle stage	4. Operation phase
Interview date:	8.12.2024

<u>Political Factors</u>

Tender Process Constraints: The German tender process creates distinct barriers to MP adoption for state-owned companies. The interviewee noted that "*depending on the size of the project, there needs to be three different offers from three different companies*" (4. Interview, 2024, 00:44:18). This bureaucratic requirement complicates the implementation of innovative circular solutions: "Knowing bureaucracy in Germany that's going to stay the same and circular construction solutions will need to adapt to that."

Economic Factors

Property Type Dependencies: The interview revealed how different real estate segments require distinct approaches to MP implementation. The interviewee explained that *"in student housing, senior housing... where there is more fluctuation, I think there it can work"* (4. Interview, 2024, 00:35:38). This insight suggests that MP adoption strategies need to be tailored to specific market segments based on tenant turnover rates and usage patterns.

Property Valuation Evolution: A novel economic driver emerged regarding real estate financing and valuation methods. The interviewee noted that "*banks are looking at this at the moment... ways to implement the relevance of the circularity of the building to the valuation*" (4. Interview, 2024, 00:19:30). This suggests that financial institutions are beginning to incorporate CE principles into their valuation models, potentially creating new economic incentives for MP adoption.

Socio-Cultural Factors

Professional Skills Gap: The interview highlighted a critical need for new professional qualifications in the CC sector. The interviewee suggested that "*instead of finished deconstructor, In the future, you have certificate 'certified circular deconstructor*'" (4. Interview, 2024, 00:41:11). This indicates a need for formal certification programs and new professional roles specifically focused on CC practices.

Technological

Factors System Integration Requirements: The interview emphasized the need for seamless integration between MPs and existing architectural workflows. The interviewee stressed the importance of being able to "*have an architect plan... be able to ideally document it pretty quickly*" (4. Interview, 2024, 00:29:23). This highlights the need for technological solutions that can bridge the gap between traditional architectural practices and MP documentation requirements.

Stage 5. End of Life

Position of the interviewee	CEO
Company	Second-Life Material Marketplace
Years of expertise	13
Market Region	Germany
Company size	SME
Life-cycle stage	5. End of Life
Interview date	03.12.2024

Political Factors

Certification System Misalignment: The interview revealed a critical misalignment in sustainability certification systems that hinders MP adoption. The interviewee noted that "*you get ten times more points if you build a bike rack in front of your building, then if you create a building passport*" (5. Interview, 2024, 00:15:27). This systemic undervaluation of MPs in certification schemes - "it brings like 1% of the whole certification" (5. Interview, 2024, 00:15:27) - creates a significant barrier to adoption.

Economic Factors

Value-Time Disconnect: A novel insight emerged regarding the temporal disconnect between investment and return. The interviewee emphasized, "*If the value you get is you get a passport... in 30 years, you can use it. I mean, now if you look at existing buildings... it makes sense, but otherwise I create a passport, I don't have any economic benefits*" (5. Interview, 2024, 00:13:17). This highlights the unusual long-term nature of selling a software like the MP, which creates immediate economic barriers.

Data Standardization Costs: The interview highlighted a specific challenge regarding standardized data requirements: "*for some parts, there's not a lot of data because you need EPDS, you need standardized data... and databases like for EPDS and so this is not in a really good quality*" (5. Interview, 2024, 00:11:10). This indicates that the cost and complexity of standardizing data represent a significant economic barrier.

Market Evolution Expectations: A unique perspective emerged regarding future market pressure: "*If you don't do that now, you cannot sell the building in five years. Because then in five years, only building passports can get sold*" (5. Interview, 2024, 00:16:56). This anticipation of future market requirements creates a different kind of social pressure for adoption.

Socio-Cultural Factors

Intrinsic Motivation Over Regulation: The interview revealed an interesting dynamic where social factors currently outweigh regulatory ones: "*most of the people using them have more like intrinsic... It's coming more about like, yeah, we have to do something, but there's not the policy*" (5. Interview, 2024, 00:09:17). This suggests that early adoption is driven more by cultural factors than regulatory requirements.

Technological Factors

Data Availability Challenge: A specific technical barrier emerged regarding the accessibility of standardized environmental data: "*there's not a lot of data because you need EPDs, you need standardized data and databases... this is not in a really good quality*" (5. Interview, 2024, 00:11:10). This highlights how the lack of standardized environmental product declarations (EPDs) and other technical data sources creates a fundamental barrier to MP implementation.

These findings highlight how MP providers face unique challenges in driving adoption, particularly around the disconnect between current certification systems, long-term value proposition, and the need for standardized data infrastructure. The insights suggest that successful MP adoption requires addressing both immediate practical barriers and longer-term systemic changes.

Stage 6. Material Information Actor

Position of the interviewee	Chief Executive Officer
Company description	Material Passport Provider
Years of expertise	6
Market Region	United Kingdom
Company size	SME
Life-cycle stage	7. Material Information Exchange
Interview date	06.12.2024

Political

Planning Process Integration: The interviewee reveals how MPs can be integrated into existing planning permission stages, with specific requirements at different phases. "Currently this is how we did it. For example, in the project we applied it, it was because of the City of London, the Council, who requested a passport" (6. Interview, 2024, 00:35:10). This extends to specific documentation requirements at different planning stages: "*part of this requirements convey that you have to create the materials passport strategy and then at stage 4 you need to give the design information, material information, deconstruction information and so on*" (6. Interview, 2024, 00:36:33).

Economic

High short-term value in commercial real estate: The interview challenges the perception that MP benefits are only long-term by highlighting rapid renovation cycles: "*in London there was a research that the average time of replacing materials, especially materials in the interior design [...], or interior space within a building… in the commercial buildings sector is 2.7 years*" (6. Interview, 2024, 00:37:40). This demonstrates immediate value rather than just end-of-life benefits.

Social

Technical Skills Gap: A specific implementation barrier emerges around the disparity between BIM-proficient users and facilities management teams: "*The, how we call them, the FM people, facilities management, mostly do not have BIM skills [...] then all this information gets lost*" (6. Interview, 2024, 00:18:03). This skills mismatch leads to significant data management challenges.

Technological

Technical Overcomplexity (Interoperability): A practical concern emerges regarding data model complexity: "*[...] currently the BIM models can have too much info and then they don't... they become unmanageable*" (6. Interview, 2024, 00:17:50). This highlights the need to balance comprehensive documentation with system usability.

BIM Independence: The interview challenges common assumptions about technological prerequisites, particularly for existing buildings: "*It is not a requirement to have a BIM in order to have MPs and models. So for example, for existing elements we can just have... like a bill of materials and building drawings.*" (6. Interview, 2024, 00:21:56). This suggests more flexible implementation pathways than previously considered.

6.1.2. Qualitative theme - based analysis across all stakeholder

Based on systematic analysis of the interview transcripts, focusing on frequency of mention and emphasis by interviewees, fundamental themes emerge as critical for MP adoption. The findings are structured according to the PEST (Political, Economic, Social, Technological) framework to provide a comprehensive understanding of the adoption landscape.

Political/Regulatory

Regulatory Integration and Planning: Integration of MPs into existing planning and tender processes emerged as a primary concern across multiple interviews. Several interviewees emphasized how MPs need to be incorporated into both municipal and national planning frameworks (Interview 6, 2024, 00:35:10; Interview 4, 2024, 00:44:18, Interview 3, 2024, 00:36:33).

Fragmentation of Standards / Overregulation Challenges: The fragmentation of standards and need for unified EU-level regulation was consistently highlighted. Interviewees stressed that current competing standards create confusion and inefficiency, with a particular emphasis on the need for EU-wide standardization rather than national approaches (Interview 3, 2024, 00:32:51; Interview 5, 2024, 00:26:24, Interview 6, 2024, 00:13:32). Interviewee 2 specifically highlighted how current building codes and regulations actively hinder circular approaches by being disproportionately large and not easy to overview (Interview 2, 2024, 00:27:31).

Asset Class Differentiation: A clear distinction emerged between implementation requirements for residential and commercial properties. This affects both technical approaches and business models, with commercial properties generally seen as more amenable to early adoption (4. Interview, 2024, 00:35:38; Interview 6, 2024, 00:35:38; 4. Interview, 2024, 00:41:11).

__**Economic**__

Short-term vs Long-term Value: The perceived lack of immediate economic benefits was identified as a key barrier, though this view varied significantly between commercial and residential sectors. While some emphasized long-term value, others pointed to rapid renovation cycles in commercial buildings as evidence of shorter-term benefits (Interview 6, 2024, 00:37:40; Interview 4, 2024, 00:19:30).

Implementation Costs: High initial implementation costs, particularly related to manual data entry and system setup, were consistently cited as significant barriers. This was especially emphasized regarding the integration with existing systems and processes (Interview 3, 2024, 00:22:12; Interview 1, 2024, 00:11:32).

__**Social/Cultural**__

Educational Requirements: The need for new professional qualifications and educational programs emerged as a crucial factor. Multiple interviewees highlighted the current lack of formal training programs and the need for specialized CE expertise (Interview 4, 2024, 00:41:11; Interview 3, 2024, 00:16:39).

__**Technological**__

System Integration: Interoperability between MPs and existing building management systems emerged as a critical barrier. The challenge of integrating with BIM systems while maintaining usability was particularly emphasized (Meliha, 2024, 00:21:58; Anastasia, 2024, 00:17:50).

Open Source and Flexibility: The need for open and flexible technological solutions was frequently cited, with particular emphasis on avoiding vendor lock-in and enabling broad industry adoption. Several interviewees challenged the assumption that advanced technologies like BIM are prerequisites for implementation (Dominik, 2024, 00:04:52; Anastasia, 2024, 00:21:56).

This PEST analysis reveals the interconnected nature of adoption barriers and highlights how progress must be coordinated across multiple dimensions to enable successful implementation.

6.1.3. Summary

The qualitative analysis across stakeholder groups reveals several key patterns in MP adoption. Technical and economic factors emerge as primary concerns, with system integration challenges and implementation costs frequently cited across interviews. The lack of standardization in both technical systems and regulatory frameworks creates significant barriers. Social and organizational factors play a more nuanced role than previously identified in literature. The analysis reveals new adoption factors such as organizational size impact and property type differentiation that significantly influence implementation success. Educational gaps emerge as a consistent theme across stakeholder groups.

The stakeholder perspectives vary significantly based on their position in the material life-cycle. While early-stage stakeholders like urban miners and manufacturers show stronger economic drivers, operational stakeholders face more complex implementation barriers. This variance suggests the need for targeted, stakeholder-specific approaches to MP adoption rather than one-size-fits-all solutions.

These findings provide a foundation for the quantitative analysis in the subsequent Sections 6.2. and 6.3.. The identified factors and patterns inform the weighted analysis framework used in Section 6.2.

6.2. Quantitative Analysis: Comparative Analysis

The following Section 6.2. will present a quantitative PEST analysis using two different methods to offer a comprehensive view through a comparative analysis of all stakeholders. While Section 6.2.1. will visually compare the weighted scores of drivers and barriers across all groups using radar charts, Section 6.2.2. will include a color-coded comparison to numerically contrast the individual adoption situations. These two approaches will help identify critical bottlenecks, which will then be visualized through a donut chart, illustrating where the flow of information within the digital CC ecosystem tends to stagnate.

Comparative Analysis Methodology

The analysis of MP adoption factors across stakeholder groups presented two critical methodological challenges. First, a direct comparison based solely on the number of factors within each PEST category (such as 6 technical versus 4 social factors) risked distorting the analysis by failing to account for the relative importance of each factor. Second, developing a framework that could simultaneously represent both the quantity and weighted importance of these factors required a more nuanced analytical approach.

Therefore, the following analysis combines both the quantity and weighted importance through a logarithmic weighting system. It calculates the average Likert-scale ratings per category, then applies a logarithmic factor based on the number of elements in each category. This addresses the quantity-quality balance while preventing larger categories from dominating the visualization. The normalization to a 30-100 scale and application of a power function enhances visual contrast, making differences between categories more apparent without distorting their relative relationships.

This method enables meaningful comparisons between stakeholder perspectives while accounting for both the breadth and perceived importance of adoption factors in each PEST category.

6.2.1. Visual comparison: Radar-chart based Analysis

Figure 10 summarizes the drivers and barriers for six key stakeholders representing different stages of the construction lifecycle based on radar charts. Each stakeholder's perspective is quantified using weighted scores on a scale of 30-100. For a more detailed and individual radar - chart analysed of each stakeholder see Appendix A2.

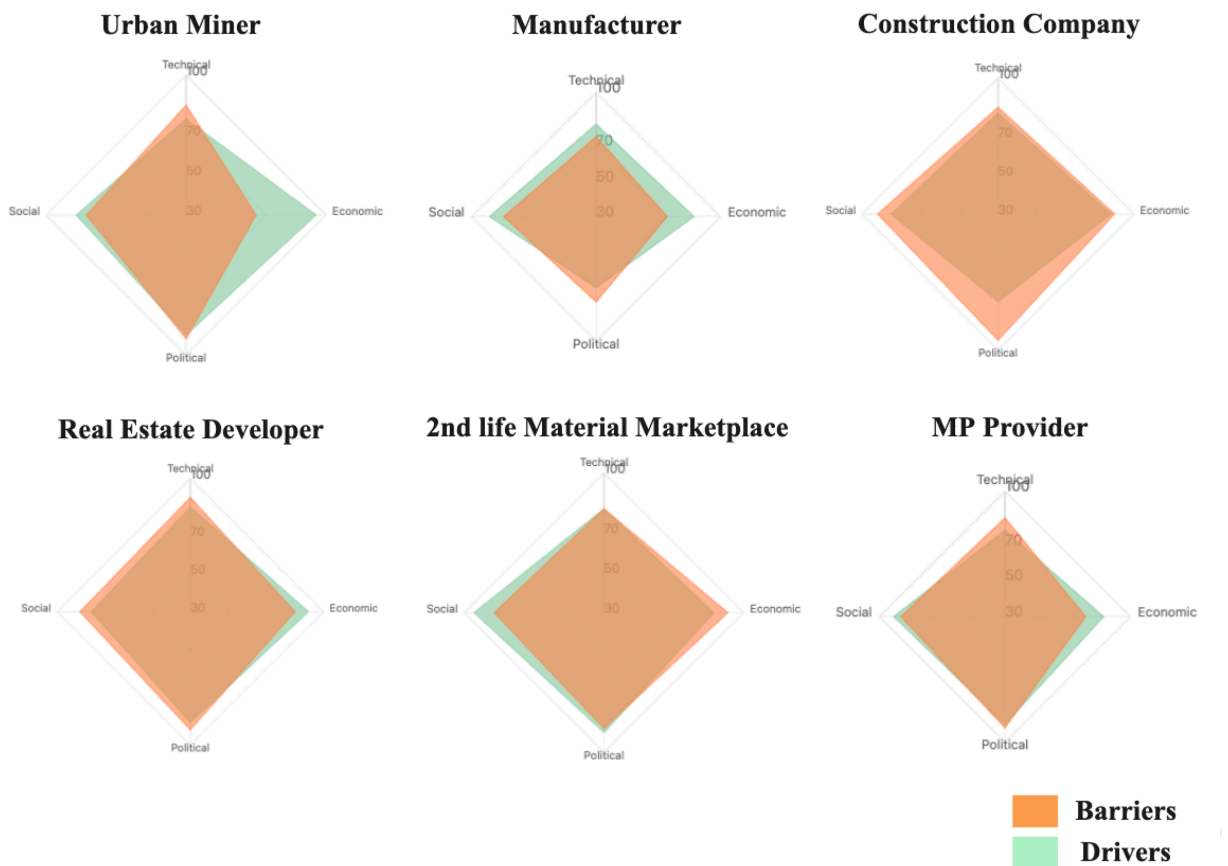

Figure 10: Radar charts of all stakeholders along the material life-cycle

Stage 1: Urban Mining

Urban miners show strong economic drivers (95) that substantially outweigh barriers (65), representing a +30 differential. However, they face technical challenges (drivers: 78, barriers: 85) and conflicting political influences (drivers: 90, barriers: 92). Social factors provide moderate positive momentum (drivers: 85, barriers: 80). While economic incentives are compelling, technical and political challenges create implementation obstacles.

Stage 2: Manufacturing / Design

Manufacturers display a generally favorable environment for MP adoption with drivers exceeding barriers in three out of four categories. Social factors show the highest driver score (90 vs 82), while economic factors demonstrate significant positive differential (85 vs 70). Only political factors present a challenge (70 vs 78). This suggests manufacturers are well-positioned for MP adoption despite some regulatory hurdles.

Stage 3: Planning / Construction

Construction companies face challenges across all PEST categories, with barriers consistently outweighing drivers. The most significant barrier is political (95 vs 75), followed by social (92 vs 85) and economic (90 vs 88). Technical factors show the smallest gap (85 vs 82). This indicates substantial implementation challenges despite recognizing MP value, with regulatory and organizational barriers being particularly problematic.

Stage 4: Operation / Maintenance

Real estate developers see economic advantages (drivers: 92, barriers: 85) but face challenges in all other domains. Technical barriers (90 vs 85), political barriers (92 vs 88), and social barriers (88 vs 82) create implementation hurdles. While property valuation benefits provide motivation, system integration challenges and regulatory obstacles currently outweigh benefits in most areas.

Stage 5: End of Life

Material Information Providers experience mixed dynamics. Strong social drivers (95 vs 85) and slight political advantages (90 vs 88) provide momentum. However, economic factors present significant challenges (85 vs 92), reflecting value-time disconnects and market evolution concerns. Technical factors show perfect equilibrium (82 vs 82), indicating balanced technological capabilities and challenges.

Stage 6: Material Information Actor

Material Information Actors show positive economic (85 vs 75) and social (92 vs 88) differentials, but face technical challenges (78 vs 85) and slight political barriers (90 vs 92). This suggests strong social and economic momentum with substantial technical implementation hurdles, particularly related to interoperability.

Across the construction value chain, the largest positive differential appears in the economic domain for Urban Miners (+30), while the largest negative differential is in the political domain for Construction Companies (-20). The most consistent pattern is seen in political factors, where nearly all stakeholders experience barriers that outweigh drivers.

6.2.2. Numerical comparison: Color-coded Analysis

In this section, a comparative quantitative analysis of the drivers and barriers to MP adoption across the six stakeholder groups will be conducted using a color-coded comparison to numerically contrast the individual adoption situations. This comparison aims to identify and quantify critical bottlenecks and systemic challenges that hinder the flow of information within the digital CC ecosystem. Finally, the section will conclude with a donut chart visualization of the results. This analysis will provide insights into how different stakeholders perceive the adoption of MPs and highlight areas where interventions are most needed to facilitate broader implementation.

While the radar plots offer a stage-aggregated visual summary of barrier concentrations across PEST dimensions, Table 15 complements this by assigning numerical values to each driver and barrier category and applying a color-coded system to highlight their relative intensity across stakeholders. This combined approach enhances the analysis by allowing for instant pattern recognition, clarifying which PEST dimensions are most influential for each actor, and enabling a comparative ranking of stakeholders from most to least incentivized to adopt MPs. It thereby supports a more targeted prioritization of intervention areas, grounded in both qualitative insight and quantitative evaluation. The following Table 15 uses color coding to help visualise the PEST category - influences on the respective stakeholders. Color coding guide:

- Green (High Drivers/low Barriers): Scores ≥ 90 indicate strong drivers/low barriers.
- Yellow (Moderate Drivers/Barriers): Scores between 75–89 indicate moderate drivers or barriers.

- Red (High Barriers/low Drivers): Scores ≥ 90 indicate significant barriers / insignificant drivers.

Stakeholder Group	Political Drivers	Political Barriers	Economic Drivers	Economic Barriers	Social Drivers	Social Barriers	Technological Drivers	Technological Barriers
Urban Mining / Recycling	90	92	95	65	85	80	78	85
Manufacturing / Design	70	78	85	70	90	82	82	75
Planning / Construction	75	95	88	90	85	92	82	85
Operation	88	92	92	85	82	88	85	90
End-of-Life	90	88	85	92	95	85	82	82
Material Information Providers	90	92	85	75	92	88	78	85

Table 15: Overall comparison of average PEST barrier- and driving factor values among all stakeholders

The following part will rank and describe the stages that are affected the most by barriers and/or missing drivers ("bottleneck stages") and those, who are least affected by barriers and positively influenced by drivers ("facilitator stages").

Bottleneck and Facilitator Stages

In order to rank the material life-cycle stages in their ability to adopt MP overall, the following Table 16 depicts the average overall count of all weighted barriers together with the average overall count of all weighted drivers. The Overall Ranking reflects the relative difficulty of MP adoption across the six stakeholder groups, based on the balance of identified drivers and barriers. A ranking of No. 1 indicates the stakeholder group for whom adoption is most challenging—i.e., the group with the highest concentration of barriers relative to enabling drivers. Conversely, a ranking of No. 6 identifies the group for whom adoption appears most feasible, supported by a comparatively favorable ratio of drivers to barriers. This ranking helps to highlight where targeted interventions are most urgently needed and where momentum for MP adoption may already be emerging. Again, Table 16 uses the above color coding to help visualise the respective factor influences on the barrier and driver dimension.

Comparison Barrier vs. Drivers	Average Barrier count	Average Driver count	Overall Ranking
Urban Mining / Recycling	80.5	87	6
Manufacturing / Design	76.25	81.75	5
Planning / Construction	90.5	82.5	1
Operation	88.75	86.75	2
End-of-Life	86.75	88	3
Material Information Providers	85	86.25	4

Table 16: Comparison and overall ranking of barrier - factors among stakeholders

The data reveals considerable variation in barrier-driver dynamics across material life-cycle stages groups within the CC industry.

Bottleneck Stages

The Planning/Construction stage emerges as the most challenged stages with an average barrier score of 90.5, contrasting with a notably lower driver score of 82.5, which positions it as the primary bottleneck in MP adoption. Operation stage follows with an average barrier score of 88.75, though showing more favorable driver conditions at 86.75. End-of-Life and Material Information Providers demonstrate moderate barrier levels at 86.75 and 85.0 respectively, balanced by comparable driver scores of 88.0 and 86.25.

This distribution suggests that the most substantial challenges are concentrated in the early and operational stages of the material flow, while design and end-use activities face relatively fewer obstacles.

Facilitator Stages

Urban Mining/Recycling and Manufacturing/Design exhibit the most favorable conditions, with significantly lower barrier scores of 80.5 and 76.25, coupled with strong driver scores of 87.0 and 81.75 respectively. The spread of 14.25 points between the highest and lowest barrier scores underscores the uneven distribution of adoption challenges across the material lifecycle stages.

This distribution implies that while certain stages face significant barriers, there are also substantial driving forces promoting MP adoption, particularly in areas related to material information, end-of-life management, and urban mining/recycling. The following section aims to visualize this dynamic.

Donut - Flow Visualization

To visualize the interplay of barriers and drivers in MP adoption across different material life-cycle stages, a circular visualization approach is proposed. This approach combines the concept of a donut chart with fluid dynamics metaphors to represent information flow blockages in the CC ecosystem.

The donut structure represents six key material life-cycle stages in the MP ecosystem arranged in a circular sequence reflecting the material and information flow in the construction lifecycle.

However, a methodological challenge emerges from the relatively narrow range of the original barrier scores obtained from the comparative analysis (typically between 75–95 on a 100-point scale). This compressed range would result in insufficient visual differentiation between stages, obscuring critical insights about relative barrier intensities. To address this limitation, a linear scaling transformation process is applied:

Step 1: Range Identification

- Original barrier range: 76.25 to 90.5 (span of 14.25 points)
- Target blockage range: 30% to 80% (span of 50 percentage points)

Step 2: Linear Transformation Formula

Blockage % = 30 + [(Original Barrier - 76.25) / 14.25] × 50

For example, in the case of Urban Mining/Recycling, the original barrier value is 80.5. Applying the transformation formula:

Blockage % = 30 + [(80.5 - 76.25) / 14.25] × 50 ≈ 44.9%

This indicates that information flow at the Urban Mining/Recycling interface experiences approximately 45% blockage, suggesting relatively favorable conditions for MP information exchange compared to stages like Planning/Construction, which exhibits 80% blockage.

Step 3: Systematic Application The transformation maintains proportional relationships while expanding visual contrast:

- Manufacturing/Design: 76.25 → **30.0%** (minimal blockage)
- Urban Mining/Recycling: 80.5 → **44.9%** (moderate blockage)
- Material Information Providers: 85.0 → **60.7%** (substantial blockage)
- End-of-Life: 86.75 → **66.8%** (high blockage)
- Operation: 88.75 → **73.9%** (severe blockage)
- Planning/Construction: 90.5 → **80.0%** (critical blockage)

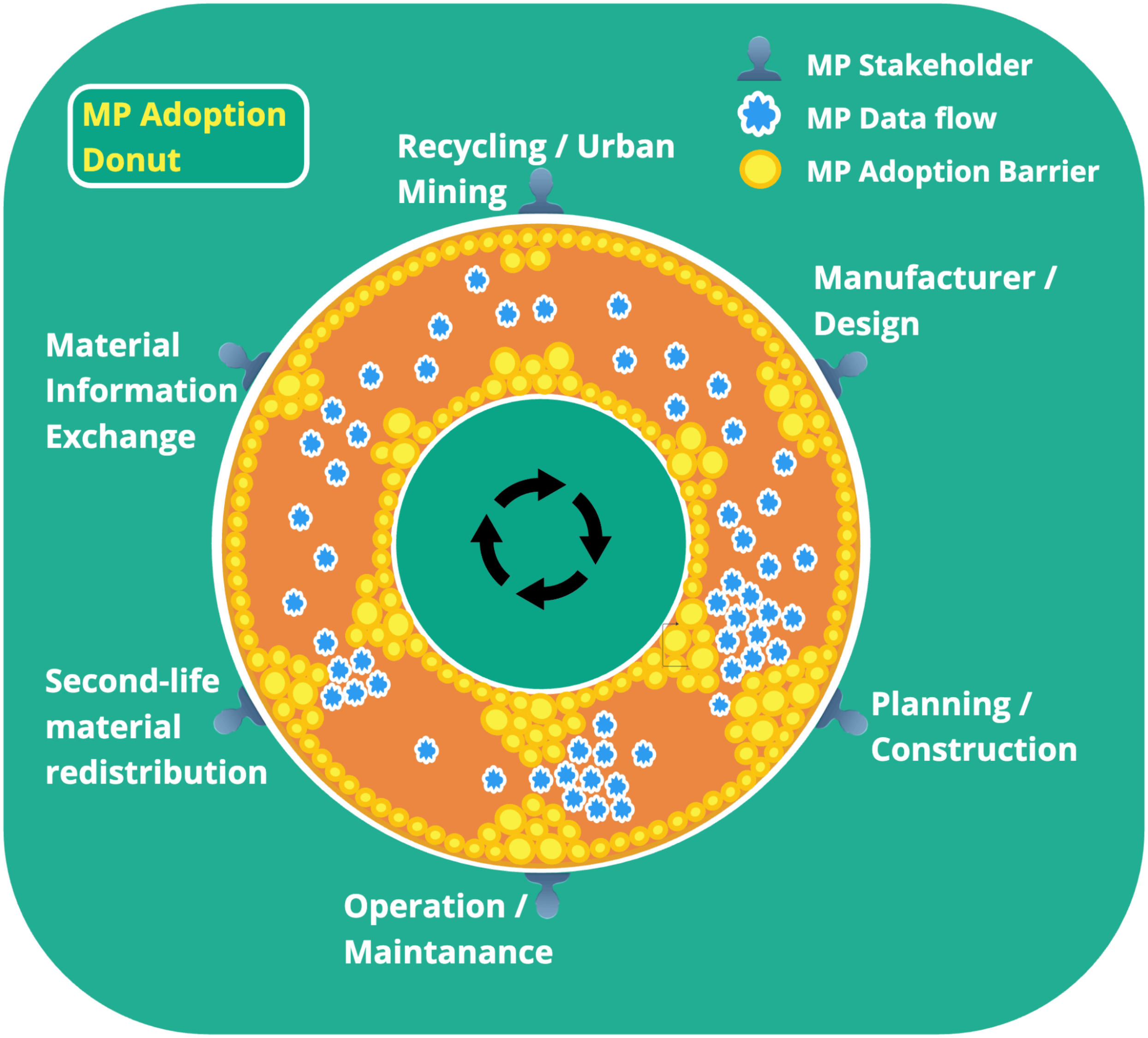

Figure 11: MP Adoption Donut - Flow Visualization of MP Adoption across all life-cycle stages

Figure 11 visualizes a comprehensive yet intuitive representation of the complex dynamics in MP adoption, highlighting both systemic bottlenecks and potential intervention points for improving information flow in the CC ecosystem.

Summary

The adoption of MPs in the construction industry is hindered by several bottleneck stages, especially the planning / construction stage and operation/maintenance stage. These stakeholders face significant organizational, regulatory, economic, and technical challenges that slow down the overall adoption process. By understanding these bottlenecks and implementing targeted strategies, the construction industry can overcome these barriers and move closer to achieving a CE.

6.3. Combined Analysis: Crucial factors and stakeholders

This section synthesizes the qualitative and quantitative analyses to identify the most critical adoption factors and stakeholder dynamics in MP implementation. By combining stakeholder-specific PEST scores with interview insights, the analysis reveals key patterns in adoption barriers and drivers across the construction industry's value chain. The synthesis is conducted in three sub-section: first identifying critical adoption factors across PEST categories (Section 6.3.1), then examining cross-domain patterns and interdependencies (Section 6.3.2), and finally analyzing bottleneck and facilitator stakeholders (Section 6.3.3).

6.3.1. Identification of high-impact adoption factors across all PEST categories

1. **Political/Regulatory Bottleneck Factors**

The need for EU and National Regulatory Standards emerged as the most consistently high-rated political factor across stakeholder groups, with 4 out of 6 stakeholders rating it as 5 on the Likert scale. This was particularly emphasized in the urban mining and construction company interviews, with scores consistently above 90 out of 100. The qualitative analysis revealed a notable insight regarding implementation hierarchy: "a lot has to come directly from the EU and then of course you can tighten the regulations according to member state... when it comes from the EU, there's no if and but" (Interview 3, 2024, 00:26:24).

Standardization Uncertainty was identified as a critical barrier, receiving 4 direct mentions in qualitative analysis. This was particularly highlighted in the manufacturer interview: "*The manufacturers say: "What do you want now? Supply chain laws already evaluate everything—now we need to fulfill the same requirements again?""* (Interview 2, 2024, 00:26:21). This uncertainty creates significant adoption hesitation across the value chain.

Over-Bureaucratization emerged as a novel barrier not previously identified in literature, with 5 direct mentions across stakeholder interviews, noting that "the entire construction industry is over-bureaucratized" (Interview 1, 2024, 00:22:41). This creates particular challenges for circular practices within existing regulatory frameworks.

2. **Economic Bottleneck Factors**

Value-Time Disconnect emerged as a significant economic challenge with 3 direct mentions in the qualitative analysis, particularly emphasized by the end-of-life stakeholder: "If the value you get is you get a passport... in 30 years, you can use it. I mean, now if you look at existing buildings... it makes sense, but otherwise I create a passport, I don't have any economic benefits" (Interview 5, 2024, 00:13:17).

New Business Models and Partnerships received high ratings from 4 out of 6 stakeholders (Likert-5), indicating strong recognition of economic opportunities.

Asset Class Differentiation was identified as a novel factor with 3 specific mentions affecting implementation strategies: "in student housing, senior housing... where there is more fluctuation, I think there it can work" (Interview 4, 2024, 00:35:38). This suggests the need for tailored approaches based on property type.

Property Valuation Evolution represents an emerging driver with 2 detailed discussions, with stakeholders noting that "banks are looking at this the moment... ways to implement the relevance of the circularity of the building to the valuation" (Interview 4, 2024, 00:19:30).

3. **Social Bottleneck Factors**

Increasing Awareness of CE Concepts received the highest consistent rating with 5 out of 6 stakeholders rating it as 5 on the Likert scale.

Professional Skills Gap emerged as a critical barrier with 4 detailed discussions, particularly regarding the disparity between BIM-proficient users and facilities management teams: "The, how we call them, the FM people, facilities management, mostly do not have BIM skills [...] then all this information gets lost" (Interview 6, 2024, 00:18:03).

Educational System Integration was identified as a fundamental challenge with 3 direct mentions: "at some universities it's still not a mandatory subject to conduct an LCA or circular economy doesn't really come up in depth anywhere in any subject" (Interview 3, 2024, 00:16:39).

Organizational Size Impact emerged as a novel factor with 2 explicit mentions affecting adoption capabilities: "in a startup that has set circular economy as a goal, it's easier to make quick changes than in a huge company that has been established for a long time" (Interview 3, 2024, 00:30:31).

4. **Technological Bottleneck Factors**

System Integration Requirements emerged as a critical factor with 4 detailed discussions, particularly regarding BIM integration: "the interface between BIM and the MP tools still doesn't work 100%" (Interview 3, 2024, 00:21:58).

Data Availability Challenge was identified as a fundamental barrier with 6 mentions (mentioned by all stakeholders): "there's not a lot of data because you need EPDs, you need standardized data and databases... this is not in a really good quality" (Interview 5, 2024, 00:11:10).

6.3.2. Cross-Domain PEST Analysis

The cross-domain analysis examines the interactions between Political, Economic, Social, and Technical factors in MP adoption, revealing critical interdependencies that shape implementation success. By analyzing factor distributions from both qualitative and quantitative data, this section identifies key combinations of barriers and drivers that require coordinated intervention. The analysis particularly focuses on novel cross-domain factors emerging from stakeholder interviews that complement existing literature, providing insights into how different PEST elements reinforce or counteract each other across the construction industry's value chain.

Distribution of High Ratings:

- Technical Domain: 38% of all Likert-5 ratings

- Political Domain: 24% of all Likert-5 ratings
- Social Domain: 22% of all Likert-5 ratings
- Economic Domain: 16% of all Likert-5 ratings

Distribution of Novel Factors by Domain:

- Technical Domain: 33% of novel mentions
- Political Domain: 28% of novel mentions
- Economic Domain: 22% of novel mentions
- Social Domain: 17% of novel mentions

This cross-domain analysis demonstrates that successful MP adoption requires coordinated intervention across PEST categories, with particular attention to technical-economic and social-technical interfaces. The distribution of high ratings and novel factors suggests that while technical aspects dominate current concerns, social and political factors play crucial supporting roles in enabling adoption.

6.3.3. Combined bottleneck- and facilitator analysis

The combined analysis reveals that both bottleneck and facilitator stakeholders are primarily concentrated in the operational stages of the material life-cycle, suggesting this stage as critical for MP adoption. The analysis integrates stakeholder-specific PEST scores with qualitative insights to identify key intervention points.

Bottleneck Stages: Building Lifecycle

Planning / Construction Stages: The results suggest that planning / construction stages represent the primary bottleneck stage in MP adoption, evidenced by their highest average barrier score (90.5) and notably lower driver score (82.5). Their challenges stem predominantly from technical integration issues, with the Chief Sustainability Officer highlighting that "the interface between BIM and the material passport tools still doesn't work" (Interview 3, 2024, 00:21:58). Organizational inertia presents a significant barrier, particularly in large enterprises where "it's easier to make quick changes than in a huge company that has been established for a long time" (Interview 3, 2024, 00:30:31). This qualitative insight aligns with the quantitative analysis showing social barriers (92) substantially exceeding drivers (85).

Operation Stage: Real estate developers emerge as the second most significant bottleneck from the combined analysis, with high barrier scores (88.75) despite relatively strong driver presence (86.75). Their challenges center on property type differentiation, as evidenced by the observation that "in student housing, senior housing... where there is more fluctuation, I think there it can work" (Interview 4, 2024, 00:35:38). Regulatory complexities create substantial barriers, particularly in tender processes where "depending on the size of the project, there needs to be three different offers from three different companies" (Interview 4, 2024, 00:44:18). This aligns with their quantitative analysis showing regulatory barriers (92) significantly outweighing drivers (88).

Facilitator Stages: Material Sourcing and Manufacturing

Urban Mining: The urban mining and recycling stages demonstrate the strongest facilitation potential, with the lowest barrier score (80.5) combined with robust driver presence (87.0). Their economic drivers (95) substantially outweigh barriers (65), supported by qualitative insights regarding supply-side innovation: "The supply is not yet good enough to justify greater demand" (Interview 1, 2024, 00:19:31). Resource security emerges as a key motivator, with political drivers (90) nearly matching barriers (92), reflecting strategic material resilience concerns.

Manufacturing and design: The manufacturing and design stage shows strong facilitator characteristics, evidenced by the second-lowest barrier score (76.25) and positive driver momentum (81.75). Their strength lies particularly in social drivers (90) versus barriers (82), indicating cultural readiness for MP adoption. The qualitative analysis reveals their unique perspective on CE integration, as one CEO emphasized the potential for material components to become assets themselves: "in the circular economy, the building component becomes the asset" (Interview 2, 2024, 00:22:55).

Summary

This distribution pattern suggests that intervention strategies should focus on operational stage stakeholders while leveraging the momentum from facilitator stakeholders in the material sourcing and manufacturing stages (as already supported by the results in Section 6.2.2).

6.4. Summary

The analysis reveals both encouraging drivers and significant barriers in MP adoption across the construction industry's stakeholder ecosystem. The quantitative PEST analysis demonstrates that while technical and political factors received the highest ratings (38% and 24% of Likert-5 ratings respectively), social factors showed the most consistent high ratings across stakeholders. This distribution suggests a growing cultural readiness for MP adoption despite technical and regulatory challenges.

The integration of qualitative and quantitative findings identified critical bottlenecks, particularly in the planning/construction phase (90.5 barrier score) and operation phase (88.75 barrier score). These operational stakeholders face significant implementation challenges, notably in system integration and regulatory compliance. These phases represent critical transition points where material information must be captured, maintained, and transferred, creating an implementation valley where even strong support from upstream and downstream stakeholders fails to bridge the practical adoption barriers.

However, the analysis also reveals promising facilitator stakeholders, particularly in urban mining/recycling (80.5 barrier score) and manufacturing/design (76.25 barrier score). These stakeholders demonstrate strong economic drivers (95) and social readiness (90), suggesting potential pathways for broader MP adoption. The emergence of new value propositions indicates evolving business models that could support adoption.

The research identifies three key areas requiring coordinated intervention:

- **Political:** Regulatory alignment through top-down MP standardization to reduce compliance fatigue and bureaucratic complexity
- **Technical:** Technical automatation and system integration (interoperability), particularly addressing the data availability challenge mentioned by all stakeholders

- **Economic**: Economic model evolution to bridge the value-time disconnect in MP implementation

These insights provide a foundation for developing targeted strategies to overcome adoption barriers and leverage existing drivers, ultimately facilitating the construction industry's transition toward circular practices.

7. Discussion

Chapter 7 examines the complex ecosystem of MP adoption, highlighting significant barriers and drivers across stakeholder groups. A notable gap (Δ14.25 points) between bottleneck and facilitator stakeholders indicates uneven progress toward CC practices, while conflicting needs around standardization, interoperability, and data ownership complicate MP governance. This chapter addresses three key questions:

- How do adoption factors align with existing research?
- What strategies can stakeholders use to overcome barriers?
- What future research questions should be prioritised to overcome the most urgent adoption barriers?

The discussion begins with a review of academic context (7.1), followed by practical strategies split into industrial (7.2.1) and policy recommendations (7.2.2). Section 7.3 explores governance models to address technical and ownership needs, while 7.4 outlines research limitations. Finally, 7.5 suggests future research directions to advance MP adoption in CC.

7.1. Academic Contributions

The adoption of MP has been confirmed as a multifaceted socio-technical transition, revealing that it is far more than a mere technical challenge, but a complex phenomenon that spans social, economic, and regulatory factors. This aligns with findings from previous studies, which also frame MP adoption as a systemic issue involving multiple stakeholders, each with different interests, requirements, and levels of engagement (Honic et al., 2021; Munaro & Tavares, 2021; van Capelleveen et al., 2023)

Research Support

This study supports several well-established factors, such as the significant barrier posed by technical integration challenges. The results emphasize the ongoing struggles with aligning existing BIM systems with MP tools, a challenge that aligns with the findings of both van Capelleveen et al. (van Capelleveen et al., 2023) and Munaro and Tavares (Munaro & Tavares, 2021), where interoperability and integration with current data systems were identified as critical technological hurdles.

Multi-stakeholder Perspective

An important contribution is made through the multi-stakeholder perspective on MP adoption, identifying critical bottlenecks (planning/construction: 90.5 barrier score) and facilitators (manufacturing: 76.25) across the material lifecycle. The qualitative analysis uncovered novel cross-domain interdependencies, such as the "value-time disconnect" that gives important nuance to Munaro et al.'s (2021) observation about perceived utility versus economic impact – revealing this perception varies significantly by stakeholder position. By quantifying information flow blockages (80% at planning/construction versus 37% at urban mining), this research demonstrates that successful MP implementation requires coordinated strategies addressing interconnected technical systems, regulatory frameworks, and economic incentives across the entire value chain – an insight insufficiently captured in previous single-stakeholder approaches.

New Factors Identified

The study uncovered several novel factors influencing MP adoption:

- **Regulatory Integration and Planning** emerged as a critical challenge, with stakeholders struggling to incorporate MPs into existing planning frameworks and tender processes.
- **Fragmentation of Standards / Overregulation Challenges** revealed how competing standards create implementation barriers, with stakeholders emphasizing that EU-wide standardization is needed rather than country-specific approaches.
- **Asset Class Differentiation** reveals higher adoption potential in commercial buildings due to faster renovation cycles.
- **Organizational Size Impact** demonstrates smaller firms' greater agility in implementation compared to established companies.
- **Professional Skills Gap** BIM-proficient designers and facilities teams lacking technical expertise to maintain MP data. This highlights the need for new professional qualifications and educational programs emerged as a crucial factor.

- **Short-term vs Long-term Value:** The perceived lack of immediate economic benefits was identified as a key barrier, though this view varied significantly between commercial and residential sectors.
- **Open-Source System Demands** highlight stakeholders' concerns about trust (transparency), vendor lock-in (monopolisation) and the need for broader industry adoption.

These discoveries significantly enhance understanding of MP implementation dynamics across the construction value chain.

7.2. Stakeholder-Specific Strategies

For Bottleneck Stakeholders (Construction Companies/Real Estate Developers):

This study shows that construction companies and real estate developers face significant barriers across all PEST categories, with the “Planning/Construction stage” showing the highest average barrier score (90.5) and the “Operation stage” close behind (88.75). These stakeholders grapple with regulatory complexity (e.g., tender process constraints) and technical integration challenges (e.g., BIM-MP interoperability).

Their challenges span immediate implementation hurdles (e.g., manual effort costs) to long-term economic drivers like property valuation evolution, suggesting a dual-focus strategy:

- **Pilot High-Impact Projects**: Lead MP adoption by initiating pilot projects in high-turnover property types (e.g., student/senior housing), demonstrating tangible benefits like enhanced property valuation.
- **System Integration**: Prioritize seamless BIM-MP tool interoperability to reduce manual effort costs. Investing in AI-driven automation could further streamline this process, mitigating technical interface challenges.
- **CE Roles**: Establish dedicated roles (e.g., "certified circular deconstructor") within organizational structures to embed circularity expertise, addressing the professional skills gap.

For Facilitator Stakeholders (Manufacturers/Urban Mining):

Manufacturers and urban miners exhibit favorable adoption conditions, with low barrier scores (Manufacturing: 76.25; Urban Mining: 80.5) and strong economic drivers (Urban Mining: 95). They benefit from cultural readiness (Manufacturing social drivers: 90) and supply-side potential.

Their strengths lie in immediate economic incentives and long-term strategic positioning (e.g., resource security), positioning them as catalysts for broader adoption:

- **Establish Circular Supply Chains**: Create supply networks that incentivize MP use, such as component-as-asset financing models, pulling demand from construction and operation stages.
- **Share Best Practices**: Act as knowledge hubs by disseminating successful MP implementation strategies, accelerating adoption among bottleneck stakeholders.
- **Standardization Leadership**: Leverage their favorable adoption conditions to lobby for industry-wide standards, reducing fragmentation.

For Material Information Providers:

Material Information Providers bridge critical data gaps but struggle with interoperability and skills mismatches. Many factors show a clear temporal dimension, from immediate technical barriers (e.g., BIM overcomplexity) to long-term value realization (e.g., commercial real estate benefits):

- **Standardization Leadership**: Leverage their role as data custodians to advocate for unified MP standards across platforms, enhancing interoperability.
- **Open-Source Platforms**: Promote open-source solutions to avoid trust and transparency considerations, and aligning with the call for flexibility.
- **Simplified Data Processes**: Develop user-friendly tools to bridge BIM and facility management gaps. Intuitive interfaces could enhance adoption among non-technical users (tackling the professional skills gap).
- **Bridging Solutions**: Offer lightweight MP alternatives (e.g., material registers) for existing buildings, broadening dissemination and accessibility.

7.3. Policy Recommendations

The transition to MPs in CC needs a differentiated policy framework. Political drivers necessitate a cohesive EU-level approach with member state adaptability, while economic, social, and technological disparities require targeted strategies. This section proposes policies that integrate regulatory coherence, economic incentives, societal engagement, and technological standardization to accelerate MP adoption across the construction value chain.

Political Factors

- **EU-Level Regulatory Framework with Local Flexibility**: Implement a unified EU MP standard to address fragmentation, allowing member states to tailor specifics.
- **Public Procurement Leadership**: Incorporate MP requirements and minimum secondary material thresholds into public tendering criteria.
- **Circularity in Norms and Permits**: Adapt building codes to prioritize circular materials and expedite permitting processes for MP-integrated projects.
- **Regulatory Sandboxes**: Establish experimental zones to test MP implementations outside restrictive regulations.

Economic Factors

- **Tax Incentives for Circularity**: Offer tax breaks for using secondary materials and increase taxes on primary resources.
- **Financing Multi-Lifecycle Value**: Develop funding mechanisms for component-based financing models, bridging the value-time gap.

Social Factors

- **Mandatory CE Education**: Integrate sustainability and circularity into all educational levels, building a skilled workforce for MP adoption.

Technological Factors

- **Standardized Data Formats**: Mandate interoperable data formats, reducing standardization costs.

- **Support for Open-Source Platforms**: Fund open-source MP tools, enhancing flexibility and accessibility.

7.4. Research Limitations

This study's exploratory approach provides valuable insights but is constrained by several factors. Its reliance on only six delphi-style interviews and surveys limits the data scope, potentially missing broader stakeholder perspectives. The geographic focus on Europe, primarily Germany and the UK, restricts generalizability to regions with differing regulatory or economic conditions.

The frequency-based methodology, weighted via a 1-5 Likert scale, may overemphasize commonly mentioned factors while undervaluing rare but critical ones. Uncertainty surrounds whether the selected experts optimally represent each life-cycle stage, possibly skewing insights. Human limitations, such as interviewees' mood swings or desire to please the interviewer, may introduce bias despite systematic efforts.

As a cross-sectional study, it captures only a snapshot of a rapidly evolving field, missing temporal trends that could emerge over time. Finally, the exclusion of perspectives from stakeholders who do not directly use MPs but affect their adoption—such as end-users like tenants, financial institutions, or policymakers—overlooks critical social, economic, and political factors beyond the industry stakeholders interviewed.

7.5. Future Research Directions

The research results point to several unresolved questions and adoption bottlenecks that signal the need for further investigation. Based on this, four key research topics are proposed:

Governance Models for Material Passports

The shift of MPs to advanced digital tools raises unresolved governance questions, driven by conflicting stakeholder needs: manufacturers seek innovation, construction firms demand standardization, urban miners need data access, and property owners protect proprietary information. The challenge is crafting a framework that balances standardisation, technical sophistication, interoperability, and data ownership across these interests. This tension, mirroring broader digital governance debates, puts top-down coordination (e.g., EU standards) against bottom-up innovation.

Potential models include centralized governance, offering consistency but risking innovation stagnation; an open-source approach, fostering adaptability but prone to fragmentation; and a commercial ecosystem, enhancing integration but inviting vendor lock-in. A hybrid "Government Standards with Open Implementation" model, where governments set standards and open-source tools drive innovation, could allow for regulatory clarity and flexibility, while addressing identified barriers. A federated system could also work, though it risks complexity and AI reliance. The hybrid model stands out, yet its feasibility remains untested. Future research must explore public-private coordination and trade-offs to validate governance for MP adoption in CC.

Economic Viability and Business Model Innovation

The identified "value-time disconnect" and short-term versus long-term value perceptions highlight economic barriers, particularly pronounced in residential versus commercial contexts. Case studies of successful MP implementations—focusing on high-turnover asset classes like commercial buildings—could yield actionable blueprints. Additionally, research into innovative financing mechanisms, such as component-based or multi-lifecycle value models, seems promising. It is needed to bridge economic gaps and align incentives across the value chain.

Stakeholder Dynamics and Broader Perspectives

The limited sample size of this study —relying on six Delphi-style interviews and surveys constrains the depth and breadth of insights about CC stakeholders. Therefore, not only perspectives from indirect influencers, such as tenants, financial institutions, and policymakers, remain underexplored, potentially overlooking critical social, economic, and political dynamics that shape MP adoption beyond direct industry actors. Also the investigated stakeholder groups are owed deeper understanding to uncover nuanced variations within these categories, such as differences by firm size, region, or project type, which the current sample may not fully capture. Future research should expand the scope to include these indirect stakeholders while increasing sample size and diversity within existing groups to ensure more robust representation. Longitudinal studies tracking stakeholder interactions over time could further address the cross-sectional limitations of this work, revealing how barriers and facilitators evolve as MPs mature in practice. Such efforts would enrich the multi-stakeholder framework and provide a more comprehensive view of adoption dynamics across the construction ecosystem.

Technological Integration and Skills Development

Technical challenges, such as BIM-MP interoperability and the professional skills gap, emerged as persistent hurdles, particularly for bottleneck stakeholders. Research should prioritize the development and testing of standardized, interoperable data formats and user-friendly open-source tools to reduce integration costs. Simultaneously, the identified need for new qualifications (e.g., CE expertise) calls for studies evaluating educational interventions and their impact on workforce readiness for MP adoption.

These research avenues promise to refine theoretical frameworks, validate practical strategies, and address the socio-technical complexities of MP implementation, paving the way for a more CC ecosystem.

8. Conclusion

This research set out to uncover the drivers and barriers of MP adoption among CC stakeholders through a mixed-methods approach, combining qualitative interviews with key actors and quantitative ranking of adoption factors. It tackles a pivotal gap in understanding how this digital tool can support the industry's shift from a linear to a CE by bridging the information gap problem.

This research revealed a significant contrast in adoption dynamics across the material life-cycle, with planning/construction and operation stages facing steep challenges—evidenced by high barrier scores of 90.5 and 88.75, respectively—stemming from issues like inadequate data availability and economic disincentives tied to long-term value realization. Conversely, urban mining and manufacturing/design emerged as frontrunners, driven by robust economic incentives—scores of 95 and 85—and a readiness to embrace circular practices, signaling their potential to lead MP uptake. These findings expose an uneven transformation pace within the construction value chain, where persistent information gaps—long identified as a critical barrier to circularity—continue to thwart progress despite MPs' capacity to deliver comprehensive, traceable material data. The PEST framework illuminated systemic hurdles, alongside untapped social momentum, painting a complex picture of adoption realities.

The broader significance of these insights lies in their reflection of the construction industry's urgent need to address its massive environmental impact—accounting for 25-40% of global CO2 emissions—amid rising sustainability pressures, like those from the Paris Agreement (UNFCCC, 2016). MPs offer a pathway to enable circular strategies such as reuse and recycling, yet their adoption demands alignment across diverse stakeholders, from raw material extractors to end-of-life managers. The distinction between bottleneck and facilitator stages suggests that focused efforts—whether improving data access for planners or harnessing urban miners' economic strengths—could trigger broader change. Real estate developers underscored asset-specific nuances, noting residential buildings' lag behind commercial ones due to tenant turnover differences, while material information providers stressed scalable data solutions, together emphasizing a need for collective action.

Compared to previous studies, which have often focused on conceptual models or individual stakeholder perspectives, this thesis offers a more applied and differentiated view on MP adoption. By combining a lifecycle-stage lens with stakeholder-specific analysis and structuring findings through the PEST framework, it contributes to a clearer understanding of where adoption is currently most constrained and which actors may support progress.

Building on this, the study offers practical recommendations for targeted strategies—such as supporting planners through regulatory alignment, enabling developers with financial incentives, and advancing digital tools for end-of-life actors, to guide more effective implementation efforts across the value chain.

This work maps the current adoption landscape and highlights a clear imperative: bridging the information divide requires not just technical tools but a differentiated perspective on stakeholder and adoption-type level to foster a unified push across the value chain. Future research could build on these findings by exploring targeted intervention strategies, longitudinal effects of MP integration, and governance innovations that align digital infrastructure with emerging policy and market trends. By revealing these dynamics, the study reaffirms the transformative potential of MPs to reduce waste and enhance resource efficiency, urging stakeholders to collaborate for a sustainable and circular built environment.

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Appendix

A1. Detailed Quantitative summary of MP adoption factors

To systematically compare the drivers and barriers affecting the adoption of MPs across all relevant stakeholder groups, this Section 4.4.5. applies the PEST framework, categorizing influencing factors as Political, Economic, Social, or Technological. The following Tables show the specific adoption factors and categorises them in the respective PEST category. Table 18 shows the detailed quantitative collection of all stakeholder perspectives on barriers to MP Adoption.

Life-cycle stage	CC actor	Type of Barrier	Name of Barrier	Sub - Amount	Total Amount
(1) Raw material extraction	**A1: Raw material supplier**	Technological	1) Quality data generation and maintenance 3) Data ownership 4) Data confidentiality 5) Data integrity and accuracy	4	**9**
		Economical	3) Insufficient Customer Demand	1	
		Political	1) Lack of regulatory frameworks	1	
		Socio-Temporal	(3) Time required for widespread adoption and integration into existing processes (4) Adapting operations to new circular practices (5) Limited experiences and success stories to drive adoption	3	
	A2: Recycler / Urban Miner	Technological	1) Quality data generation and maintenance 3) Data ownership 4) Data confidentiality 5) Data integrity and accuracy	4	**12**
		Economical	3) Insufficient Customer Demand	1	
		Political	1) Lack of regulatory frameworks 2) Absence of laws specifying passport requirements and use 4)Insufficient stimulation of CE demand (6) Compliance issues with CE-based materials	4	
		Socio-Temporal	(3) Time required for widespread adoption and integration into existing processes (4) Adapting operations to new circular practices (5) Limited experiences and success stories to drive adoption	3	
(2) Manufacturing/ Design	**A3: Component designers**	Technological	1) Quality data generation and maintenance 3) Data ownership 4) Data confidentiality 5) Data integrity and accuracy	4	**19**
		Economical	1) Upfront capital Expenditure 2) High operating costs of data registration 3) Insufficient Customer Demand	3	

		Political	1) Lack of regulatory frameworks (2) Absence of laws specifying passport requirements and use (4) Insufficient stimulation of CE demand (6) Compliance issues with CE-based materials (7) Conflicting environmental policies (8) Absence of legal warranty and quality assurance for CE-based products	6	
		Socio-Temporal	(1) Lack of trust between firms hindering information exchange (2) Reluctance to share certain information due to business competition (3) Time required for widespread adoption and integration into existing processes (4) Adapting operations to new circular practices (5) Limited experiences and success stories to drive adoption" (6) Misalignment between short-term business goals and long-term sustainability benefits	6	
	A4: Component manufacturers	Technological	1) Quality data generation and maintenance 3) Data ownership 4) Data confidentiality 5) Data integrity and accuracy	4	**20**
		Economical	1) Upfront capital Expenditure 2) High operating costs of data registration 3) Insufficient Customer Demand	3	
		Political	1) Lack of regulatory frameworks (2) Absence of laws specifying passport requirements and use (4) Insufficient stimulation of CE demand (5) Lack of legal right to repair for firms and consumers (6) Compliance issues with CE-based materials (7) Conflicting environmental policies (8) Absence of legal warranty and quality assurance for CE-based products	7	
		Socio-Temporal	(1) Lack of trust between firms hindering information exchange (2) Reluctance to share certain information due to business competition (3) Time required for widespread adoption and integration into existing processes (4) Adapting operations to new circular practices (5) Limited experiences and success stories to drive adoption" (6) Misalignment between short-term business goals and long-term sustainability benefits	6	
(3) Planning/ Construction	**A5&A6: Planners (Architects/Engineers)**	Technological	1) Quality data generation and maintenance 3) Data ownership 4) Data confidentiality 5) Data integrity and accuracy	4	**17**
		Economical	1) Upfront capital Expenditure 2) High operating costs of data registration 3) Insufficient Customer Demand	3	
		Political	1) Lack of regulatory frameworks (2) Absence of laws specifying passport requirements and use (6) Compliance issues with CE-based materials (7) Conflicting environmental policies	4	
		Socio-Temporal	(1) Lack of trust between firms hindering information exchange (2) Reluctance to share certain information due to business competition (3) Time required for widespread adoption and integration into existing processes	6	

			(4) Adapting operations to new circular practices (5) Limited experiences and success stories to drive adoption" (6) Misalignment between short-term business goals and long-term sustainability benefits		
	A7: Construction company	Technological	1) Quality data generation and maintenance 3) Data ownership 4) Data confidentiality 5) Data integrity and accuracy	4	**15**
		Economical	3) Insufficient Customer Demand	1	
		Political	1) Lack of regulatory frameworks (2) Absence of laws specifying passport requirements and use (6) Compliance issues with CE-based materials (7) Conflicting environmental policies	4	
		Socio-Temporal	(1) Lack of trust between firms hindering information exchange (2) Reluctance to share certain information due to business competition (3) Time required for widespread adoption and integration into existing processes (4) Adapting operations to new circular practices (5) Limited experiences and success stories to drive adoption" (6) Misalignment between short-term business goals and long-term sustainability benefits	6	
(4) Operation/ Maintenance	**A8: Building Owner**	Technological	1) Quality data generation and maintenance 3) Data ownership 4) Data confidentiality 5) Data integrity and accuracy	4	**15**
		Economical	1) Upfront capital Expenditure 2) High operating costs of data registration 3) Insufficient Customer Demand	3	
		Political	1) Lack of regulatory frameworks (2) Absence of laws specifying passport requirements and use (4) Insufficient stimulation of CE demand (5) Lack of legal right to repair for firms and consumers (8) Absence of legal warranty and quality assurance for CE-based products	5	
		Socio-Temporal	(3) Time required for widespread adoption and integration into existing processes (4) Adapting operations to new circular practices (5) Limited experiences and success stories to drive adoption	3	
(5) End of Life	**A9: Dismantling firm**	Technological	1) Quality data generation and maintenance 3) Data ownership 4) Data confidentiality 5) Data integrity and accuracy	4	**11**
		Economical	3) Insufficient Customer Demand	1	
		Political	1) Lack of regulatory frameworks (4) Insufficient stimulation of CE demand (6) Compliance issues with CE-based materials	3	
		Socio-Temporal	(3) Time required for widespread adoption and integration into existing processes (4) Adapting operations to new circular practices (5) Limited experiences and success stories to drive adoption	3	

	A10: Redistributors of second-life materials	Technological	1) Quality data generation and maintenance 3) Data ownership 4) Data confidentiality 5) Data integrity and accuracy	4	**12**
		Economical	3) Insufficient Customer Demand	1	
		Political	1) Lack of regulatory frameworks (2) Absence of laws specifying passport requirements and use (4) Insufficient stimulation of CE demand (6) Compliance issues with CE-based materials (8) Absence of legal warranty and quality assurance for CE-based products	4	
		Socio-Temporal	(3) Time required for widespread adoption and integration into existing processes (4) Adapting operations to new circular practices (5) Limited experiences and success stories to drive adoption	3	
(6) Logistics / Reverse Logistics	**A11: Logistics Firm**	Technological	1) Quality data generation and maintenance 3) Data ownership 4) Data confidentiality 5) Data integrity and accuracy	4	**9**
		Economical	3) Insufficient Customer Demand	1	
		Political	(6) Compliance issues with CE-based materials	1	
		Socio-Temporal	(3) Time required for widespread adoption and integration into existing processes (4) Adapting operations to new circular practices (5) Limited experiences and success stories to drive adoption	3	
(7) Material Information Exchange	**A12: Material Passport Operator**	Technological	1) Quality data generation and maintenance 2) Standardized Data exchange 3) Data ownership 4) Data confidentiality 5) Data integrity and accuracy	5	**14**
		Economical	3) Insufficient Customer Demand	1	
		Political	1) Lack of regulatory frameworks (2) Absence of laws specifying passport requirements and use (3) Limited government participation in passport design (6) Compliance issues with CE-based materials (7) Conflicting environmental policies	5	
		Socio-Temporal	(3) Time required for widespread adoption and integration into existing processes (4) Adapting operations to new circular practices (5) Limited experiences and success stories to drive adoption	3	

Table 18: Quantitative collection of all stakeholder perspectives on barriers to MP Adoption

Table 19 shows the detailed quantitative collection of all stakeholder perspectives on barriers to MP Adoption.

Life-cycle stage	CC actor	Type of Driver	Name of Drivers	Sub - Amoun	Total Amount

				t	
(1) Raw material extraction	**A1: Raw material supplier**	Technological	4) Blockchain Technology	1	**9**
		Economical	11) Tax incentives due to Regulatory Compliance	1	
		Political	1) Mandatory EU laws 2) EU and German Policy Frameworks	2	
		Socio-Temporal	(1) Increasing awareness of CE concepts (2) Growing recognition of the value of material and product information (3) Shift towards more sustainable and responsible resource management (4) Evolving consumer preferences for sustainable products and practices (5) Technological advancements enabling better data collection and management	5	
	A2: Recycler / Urban Miner	Technological	2) Internet of Things implementations (IoT). 4) Blockchain Technology 5) Incorporation of sensors in Materials	3	**16**
		Economical	2) Creation of Secondary Material Market 6) Market differential 8) New business models and partnerships 11) Tax incentives due to Regulatory Compliance 12) Enhanced Decision-Making and Planning	5	
		Political	1) Mandatory EU laws 2) EU and German Policy Frameworks 4) Research Support	3	
		Socio-Temporal	(1) Increasing awareness of CE concepts (2) Growing recognition of the value of material and product information (3) Shift towards more sustainable and responsible resource management (4) Evolving consumer preferences for sustainable products and practices (5) Technological advancements enabling better data collection and management	5	
(2) Manufacturing/ Design	**A3: Component designers**	Technological	1) Building Information Modeling (BIM) 2) Internet of Things implementations (IoT) 3) Advanced Digital Integration Platforms 4) Blockchain Technology 5) Incorporation of sensors in Materials	5	**18**
		Economical	6) Market differential 7) Protection against industrial counterfeiting, tampering and misuse 8) New business models and partnerships 11) Tax incentives due to Regulatory Compliance 12) Enhanced Decision-Making and Planning	5	
		Political	1) Mandatory EU laws 2) EU and German Policy Frameworks 3) EU and German Guidelines and Strategies 4) Research Support	4	
		Socio-Temporal	(1) Increasing awareness of CE concepts (2) Growing recognition of the value of material and product information (3) Shift towards more sustainable and responsible resource	4	

			management (5) Technological advancements enabling better data collection and management		
	A4: Component manufacturers	Technological	1) Building Information Modeling (BIM) 2) Internet of Things implementations (IoT) 3) Advanced Digital Integration Platforms 4) Blockchain Technology 5) Incorporation of sensors in Materials	5	**20**
		Economical	1) Creation of Secondary Market 6) Market differential 7) Protection against industrial counterfeiting, tampering and misuse 8) New business models and partnerships 10) Tax Benefits through decreased environmental footprint 11) Tax incentives due to Regulatory Compliance 12) Enhanced Decision-Making and Planning	7	
		Political	1) Mandatory EU laws 2) EU and German Policy Frameworks 3) EU and German Guidelines and Strategies 4) Research Support	4	
		Socio-Temporal	(1) Increasing awareness of CE concepts (2) Growing recognition of the value of material and product information (3) Shift towards more sustainable and responsible resource management (5) Technological advancements enabling better data collection and management	4	
(3) Planning/ Construction	**A5&A6: Planners (Architects/Engineers)**	Technological	1) Building Information Modeling (BIM) 2) Internet of Things implementations (IoT) 3) Advanced Digital Integration Platforms. 4) Blockchain Technology 5) Incorporation of sensors in Materials	5	**17**
		Economical	6) Market Diffrential. 8) New business models and partnerships 10) Tax Benefits through decreased environmental footprint 11) Tax incentives due to Regulatory Compliance 12) Enhanced Decision-Making and Planning	5	
		Political	2) EU and German Policy Frameworks 3) EU and German Guidelines and Strategies 4) Research Support"	3	
		Socio-Temporal	(1) Increasing awareness of CE concepts (2) Growing recognition of the value of material and product information (3) Shift towards more sustainable and responsible resource management (5) Technological advancements enabling better data collection and management	4	
	A7: Construction company	Technological	1) Building Information Modeling (BIM) 2) Internet of Things implementations (IoT) 3) Advanced Digital Integration Platforms. 4) Blockchain Technology 5) Incorporation of sensors in Materials	5	**17**

		Economical	A6) Market differential A8) New business models and partnerships A10) Tax Benefits through decreased environmental footprint A11) Tax incentives due to Regulatory Compliance A12) Enhanced Decision-Making and Planning	5	
		Political	2) EU and German Policy Frameworks 3) EU and German Guidelines and Strategies 4) Research Support"	3	
		Socio-Temporal	(1) Increasing awareness of CE concepts (2) Growing recognition of the value of material and product information (3) Shift towards more sustainable and responsible resource management (5) Technological advancements enabling better data collection and management	4	
(4) Operation/ Maintenance	**A8: Building Owner**	Technological	1) Building Information Modeling (BIM) 2) Internet of Things implementations (IoT) 3) Advanced Digital Integration Platforms 4) Blockchain Technology 5) Incorporation of sensors in Materials	5	**17**
		Economical	1) Improved asset management 2) Time saving in maintenance 3) Decrease of failure cost 4) Efficiency of construction process	4	
		Political	2) EU and German Policy Frameworks 3) EU and German Guidelines and Strategies 4) Research Support"	3	
		Socio-Temporal	(1) Increasing awareness of CE concepts (2) Growing recognition of the value of material and product information (3) Shift towards more sustainable and responsible resource management (4) Evolving consumer preferences for sustainable products and practices (5) Technological advancements enabling better data collection and management	5	
(5) End of Life	**A9: Dismantling firm**	Technological	1) Building Information Modeling (BIM) 2) Internet of Things implementations (IoT) 3) Advanced Digital Integration Platforms 4) Blockchain Technology 5) Incorporation of sensors in Materials	5	**16**
		Economical	1) Creation of Secondary Material Market 6) Market Diffrential 8) New business models and partnerships 10) Tax Benefits through decreased environmental footprint 11) Tax incentives due to Regulatory Compliance	5	
		Political	1) Mandatory EU laws 4) Research Support	2	
		Socio-Temporal	(1) Increasing awareness of CE concepts (2) Growing recognition of the value of material and product information (3) Shift towards more sustainable and responsible resource management (5) Technological advancements enabling better data collection and management	4	

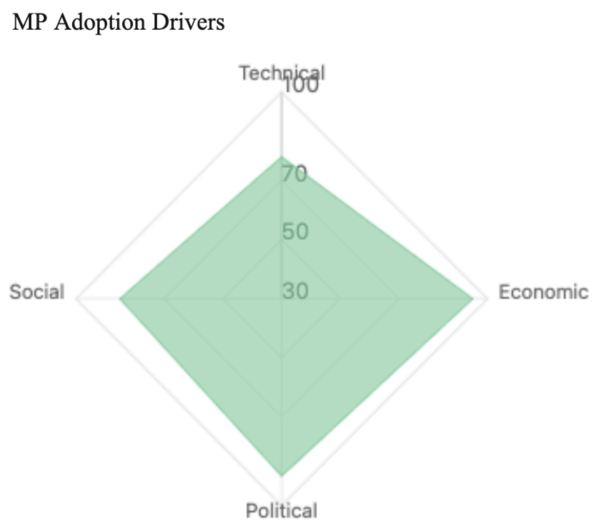
	A10: Redistributors of second-life materials	Technological	1) Building Information Modeling (BIM) 2) Internet of Things implementations (IoT) 3) Advanced Digital Integration Platforms 4) Blockchain Technology 5) Incorporation of sensors in Materials	5	**17**
		Economical	1) Creation of Secondary Material Market 6) Market differential 8) New business models and partnerships 11) Tax incentives due to Regulatory Compliance	4	
		Political	1) Mandatory EU laws 2) EU and German Policy Frameworks 3) EU and German Guidelines and Strategies 4) Research Support	4	
		Socio-Temporal	(1) Increasing awareness of CE concepts (2) Growing recognition of the value of material and product information (3) Shift towards more sustainable and responsible resource management (5) Technological advancements enabling better data collection and management	4	
(6) Logistics / Reverse Logistics	**A11: Logistics Firm**	Technological	2) Internet of Things implementations (IoT) 4) Blockchain Technology 5) Incorporation of sensors in Materials	3	**10**
		Economical	6) Market differential 8) New business models and partnerships 11) Tax incentives due to Regulatory Compliance	3	
		Political	/	0	
		Socio-Temporal	(1) Increasing awareness of CE concepts (2) Growing recognition of the value of material and product information (3) Shift towards more sustainable and responsible resource management (5) Technological advancements enabling better data collection and management	4	
(7) Material Information Exchange	**A12: Material Passport Operator**	Technological	2) Internet of Things implementations (IoT). 3) Advanced Digital Integration Platforms 4) Blockchain Technology 5) Incorporation of sensors in Materials	4	**13**
		Economical	8) New business models and partnerships	1	
		Political	1) Mandatory EU laws 2) EU and German Policy Frameworks 3) EU and German Guidelines and Strategies 4) Research Support	4	
		Socio-Temporal	(1) Increasing awareness of CE concepts (2) Growing recognition of the value of material and product information (3) Shift towards more sustainable and responsible resource management (5) Technological advancements enabling better data collection and management	4	

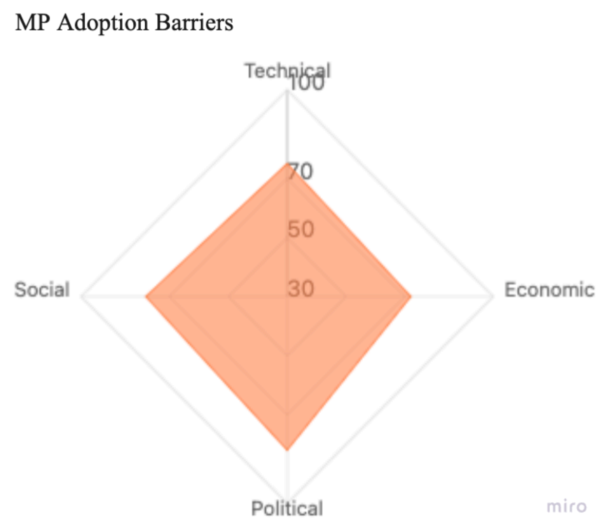
Table 19: Quantitative collection of all stakeholder perspectives on barriers to MP Adoption

A2. Individual radar - chart based adoption Perspectives towards MP

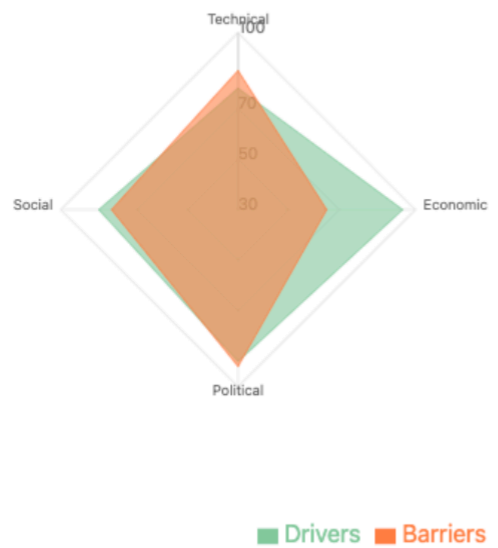
Based on this method, the following analysis will map the drivers and barriers for each interviewed stakeholders representing one stakeholder group using radar charts and comparing the solely quantitative insights from the literature analysis with the weighted values given by the interviewees to each adoption factor.

Stage 1: Urban Mining





The PWC score analysis of urban miner perspectives shows a more nuanced picture of drivers and barriers' influence. Only two out of four PEST categories demonstrate higher driver scores. Most significantly, economic drivers (95) substantially outweigh their barriers (65), representing the largest positive differential of 30 points. Technical factors reveal an inverse relationship, with barriers (85) exceeding drivers (78), indicating substantial implementation challenges. The political domain shows the highest intensity of both drivers (90) and barriers (92), with barriers slightly predominating, suggesting strong but conflicting regulatory influences. Social factors demonstrate a moderate positive balance with drivers (85) marginally outweighing barriers (80). When examining the spread of scores, drivers show a broader range (78-95) compared to barriers (65-92), while also achieving higher average scores. However, the magnitude of differences between drivers and barriers varies considerably across categories, from +30 in the economic domain to -7 in the technical domain. This suggests that while urban miners face significant technical and political challenges, strong economic incentives and balanced social factors provide a foundation for Material Passport adoption, although the path forward appears more complex than for manufacturers.

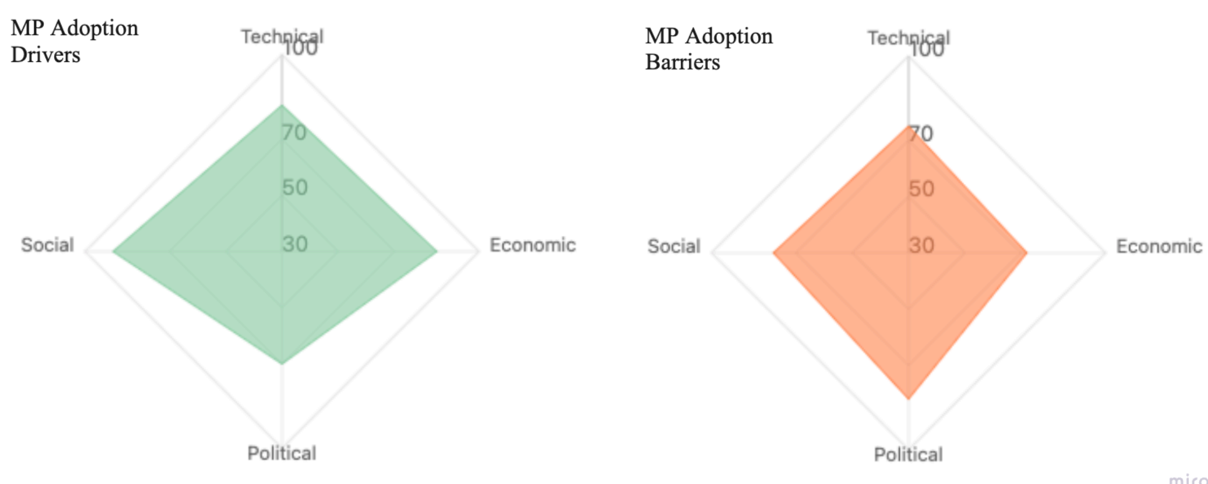


Detailed Category Analysis

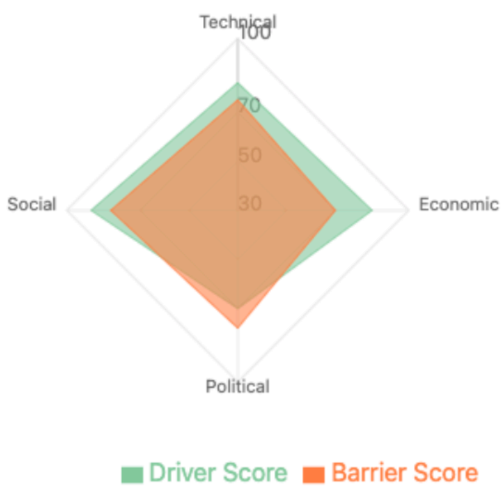
CATEGORY	DRIVER SCORE	BARRIER SCORE	NET SCORE
Technical	78	85	-7.0
Economic	95	65	30.0
Political	90	92	-2.0
Social	85	80	5.0

miro

Stage 2: Manufacturing / Design



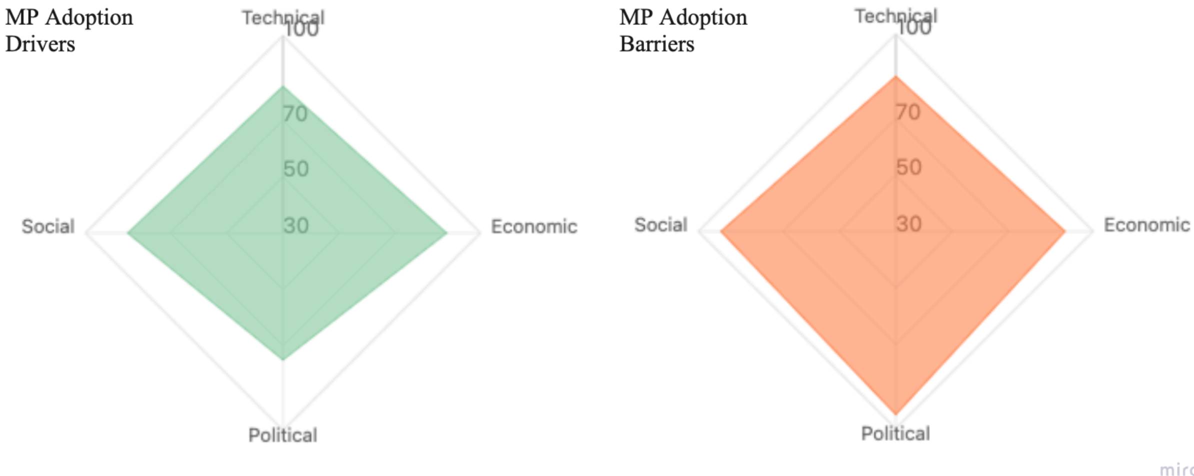
The PWC score analysis of manufacturer perspectives reveals that drivers generally exert more influence than barriers, with three out of four PEST categories showing higher driver scores. Most notably, economic drivers (85) significantly outweigh their barriers (70), while social drivers achieve the highest absolute score (90) compared to their barriers (82). Only in the political domain do barriers (78) exceed drivers (70), indicating regulatory challenges. Technical factors show a moderate advantage for drivers (82 vs 75). When considering both the spread of scores and the magnitude of differences, the drivers (ranging from 70-90) demonstrate slightly stronger overall influence than barriers (ranging from 70-82), suggesting a generally favorable environment for Material Passport adoption despite significant challenges. This is particularly evident in the total aggregate scores across all categories, where drivers consistently show higher or comparable influence levels except in the political domain.



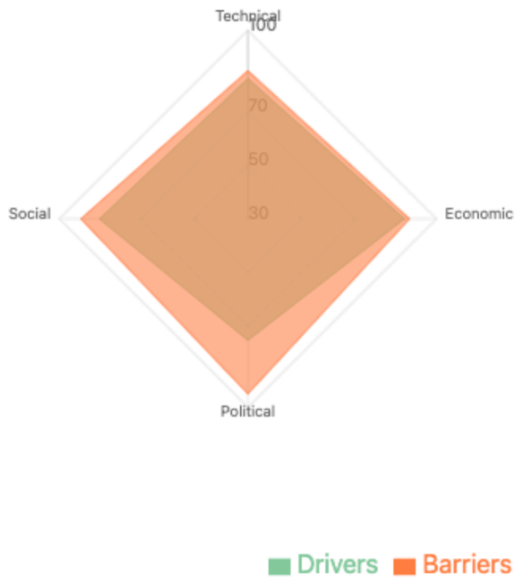
Detailed Category Analysis

CATEGORY	DRIVER PWC SCORE	BARRIER PWC SCORE	FACTOR COUNT (D/B)
Technical	82	75	7/4
Economic	85	70	8/3
Political	70	78	5/7
Social	90	82	3/6

Stage 3. Planning / Construction



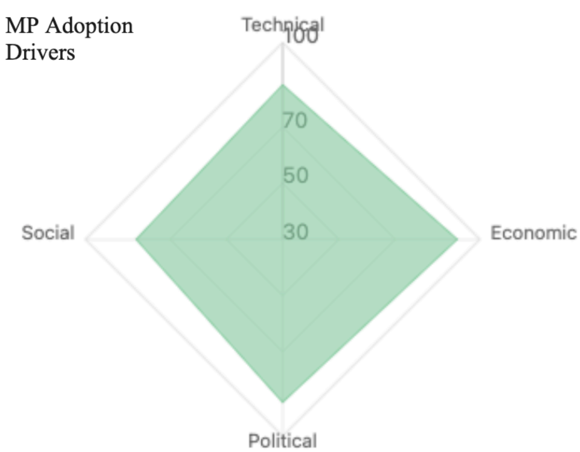
The weighted analysis of the construction company perspective reveals that barriers generally exert more influence than drivers across all PEST categories. Most notably, political barriers (95) substantially outweigh their drivers (75), showing the largest negative differential of -20 points. This is followed by the social domain, where barriers (92) exceed drivers (85) by -7 points, indicating significant organizational and educational challenges. Economic factors show a similar pattern with barriers (90) slightly higher than drivers (88), suggesting that despite strong economic incentives, technical interface challenges pose significant obstacles. Technical factors demonstrate the smallest gap, with barriers (85) marginally exceeding drivers (82), indicating a relatively balanced technological landscape. When examining the spread of scores, barriers show a higher range (85-95) compared to drivers (75-88), while also achieving consistently higher absolute scores. This suggests that while the construction company sees value in Material Passport adoption, they face substantial implementation challenges across all domains, with political and social barriers being particularly significant hurdles to overcome.

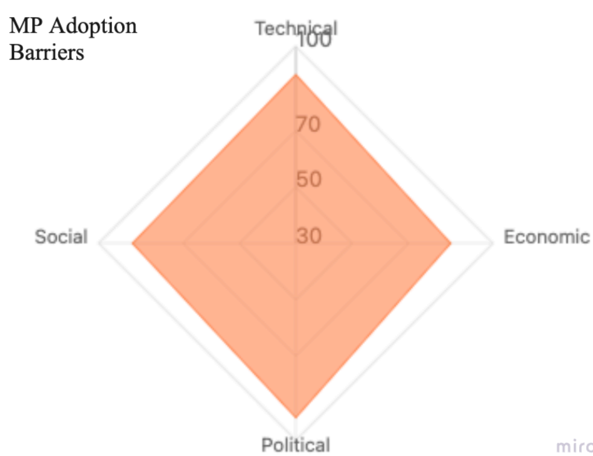


Detailed Category Analysis

CATEGORY	DRIVER SCORE	BARRIER SCORE	NET SCORE
Technical	82	85	-3.0
Economic	88	90	-2.0
Political	75	95	-20.0
Social	85	92	-7.0

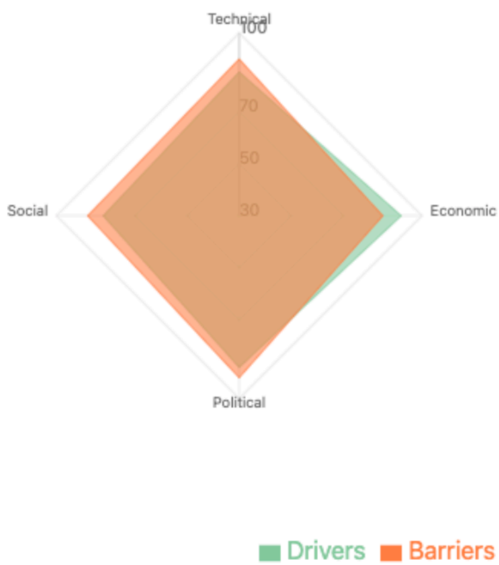
Stage 4. Operation / Maintenance





The weighted analysis of real estate developer perspectives reveals that barriers generally outweigh drivers across most PEST categories. Economic factors present the only positive differential, with drivers (92) exceeding barriers (85) by +7 points, primarily due to strong asset management potential and property valuation benefits. However, in all other domains, barriers predominate: Political barriers (92) surpass drivers (88) by -4 points, reflecting significant regulatory and tender process challenges. Technical barriers (90) exceed drivers (85) by -5 points, indicating substantial system integration challenges despite strong technological enablers. The most pronounced gap appears in the social domain, where barriers (88) outweigh drivers

(82) by -6 points, highlighting significant cultural and skills-related challenges. When examining the spread of scores, both drivers (82-92) and barriers (85-92) show relatively high ranges, with consistently strong intensity across all categories. This suggests that while real estate developers see significant value potential in Material Passport adoption, they face substantial implementation challenges that currently outweigh the benefits in most areas, with economic advantages being the primary motivating factor.

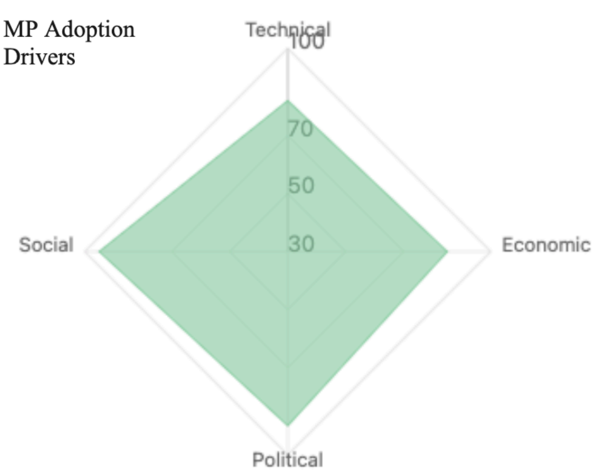


Detailed Category Analysis

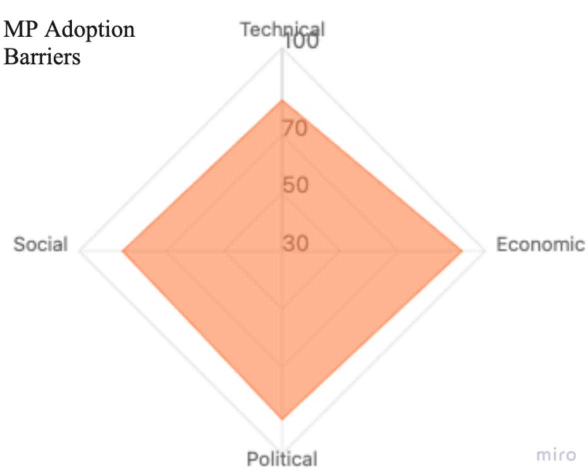
CATEGORY	DRIVER SCORE	BARRIER SCORE	NET SCORE
Technical	85	90	-5.0
Economic	92	85	7.0
Political	88	92	-4.0
Social	82	88	-6.0

Stage 5. End of Life

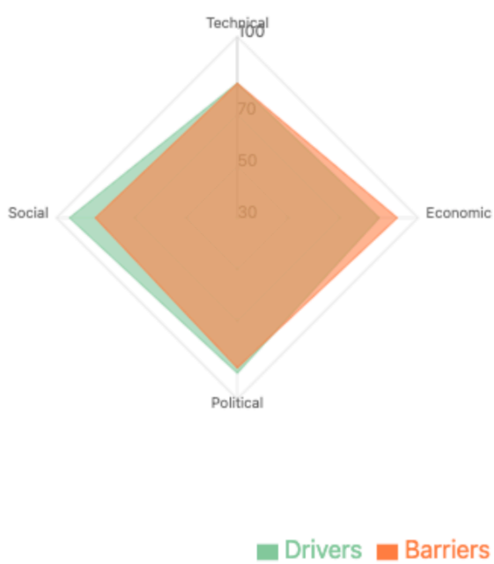
MP Adoption Drivers



MP Adoption Barriers



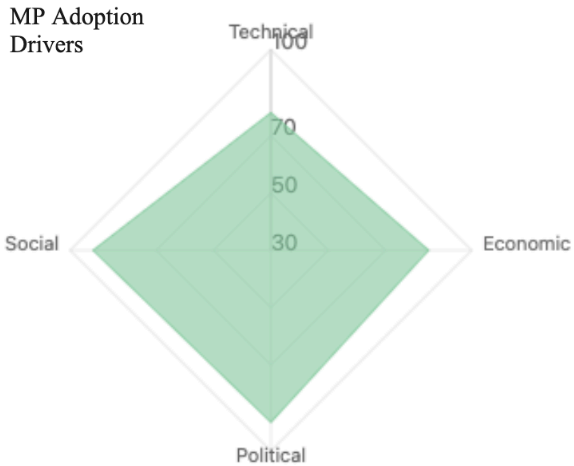
The weighted analysis of Material Information Provider perspectives reveals a mixed landscape with varying dominance between drivers and barriers across PEST categories. Social factors show the strongest positive differential, with drivers (95) significantly outweighing barriers (85) by +10 points, primarily driven by strong intrinsic motivation and awareness factors. Political factors also show a slight positive balance with drivers (90) marginally exceeding barriers (88) by +2 points, indicating that regulatory support slightly outweighs challenges. However, economic factors display the most significant negative differential, with barriers (92) substantially exceeding drivers (85) by -7 points, reflecting serious concerns about value-time disconnect and market evolution. Technical factors show perfect equilibrium (82 vs 82), suggesting that technological capabilities and challenges are equally balanced. When examining the spread of scores, drivers show a broader range (82-95) compared to barriers (82-92), indicating more variability in enabling factors. This suggests that while Material Information Providers see strong social and political momentum for Material Passport adoption, they face significant economic hurdles that need to be addressed for successful implementation.

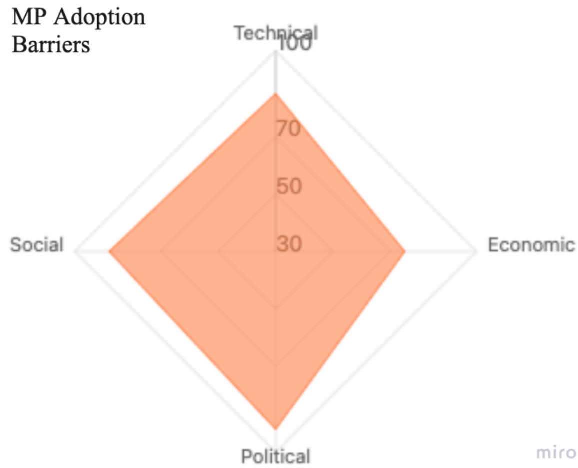


Detailed Category Analysis

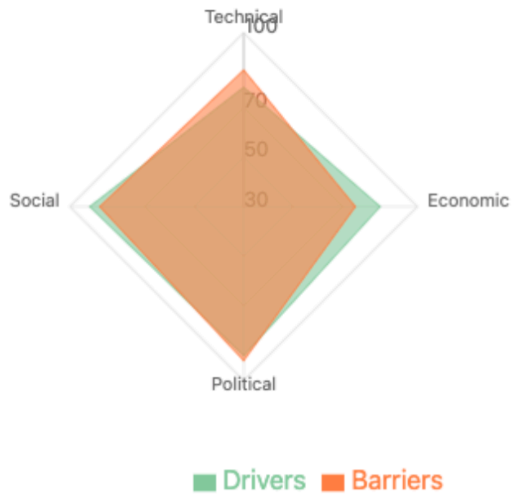
CATEGORY	DRIVER SCORE	BARRIER SCORE	NET SCORE
Technical	82	82	0.0
Economic	85	92	-7.0
Political	90	88	2.0
Social	95	85	10.0

Stage 6. Material Information Actor





The weighted analysis of Material Information Provider perspectives reveals varying dynamics across PEST categories. Social factors show strong driver influence (92) with slightly lower barriers (88), yielding a positive differential of +4 points. Economic factors demonstrate the most favorable balance with drivers (85) exceeding barriers (75) by +10 points, enhanced by the recognition of short-term commercial value. However, both technical and political domains show challenges. Technical factors reveal a negative differential with drivers (78) being outweighed by barriers (85) by -7 points, particularly due to interoperability concerns. Political factors show the smallest positive margin, with drivers (90) nearly matched by barriers (92), reflecting the impact of planning process integration challenges. This analysis suggests that while Material Information Providers have strong social and economic momentum, they face significant technical and political implementation hurdles.



CATEGORY	DRIVER SCORE	BARRIER SCORE	NET SCORE
Technical	78	85	-7.0
Economic	85	75	10.0
Political	90	92	-2.0
Social	92	88	4.0

This chapter presents a quantitative PEST analysis of Material Passport (MP) adoption across the construction industry value chain. The analysis employs a weighted radar chart visualization method that balances both the quantity and rated importance of adoption factors through a logarithmic weighting system. This approach addresses methodological challenges related to varying factor counts across PEST categories while enabling meaningful stakeholder comparisons.

A3. Quantitative Data Overview

This qualitative part of this research is based on six semi-structured expert interviews conducted to explore the real-world conditions under which MPs are adopted or resisted across the building material life cycle. Each interviewee represents one key stakeholder group positioned along different lifecycle stages (see Figure 7). The interviews were held in December 2024 and ranged from approximately 45 to 75 minutes in length. Participants were selected for their professional engagement with MPs or closely related circular practices and technologies. Thematic coding of the interview transcripts formed the basis for identifying adoption drivers, stage-specific barriers, and the broader systemic and regulatory conditions influencing uptake across the sector. The following tables give an overview of each interview.

1. Interview Transcript Urban Mining Company (german)

Name	Anonymous
Position of the interviewee	Project Manager
Company	Urban Mining Company
Company size	Medium sized company
Life-cycle stage	1. Raw Material Extraction
Interview date:	16.12.2024

2. Interview Transcript: Circular Material Manufacturer (german)

Name	Anonymised
Position of the interviewee	CEO
Company	Circular Material Manufacturer
Company size	SME
Life-cycle stage	2. Manufacturing / Design

Interview date:	02.12.2024

3. Interview Transcript Construction Company (german)

Name	Anonymous
Position of the interviewee	Chief Sustainability Officer
Company	Construction Company
Company size	Large company
Life-cycle stage	3. Planning / Construction
Interview date:	06.12.2024

4. Interview Transcript: Real Estate Developer (english)

Name	Anonymised
Position of the interviewee	Sustainability Manager
Company	Residential Real Estate Developer
Company size	Large-sized company
Life-cycle stage	4. Operation phase
Interview date:	8.12.2024

5. Interview Transcript: Redistributor of second-life materials (english)

Name	Anonymised
Position of the interviewee	CEO
Company	Second-Life Material Marketplace
Company size	SME
Life-cycle stage	5. End of Life

Interview date	03.12.2024

6. Interview Transcript: Material Passport Provider (english)

Name	Anonymised
Position of the interviewee	CEO
Company description	Material Passport Provider
Company size	SME
Life-cycle stage	7. Material Information Exchange
Interview date	06.12.2024