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Master Thesis

Digital Product Passport

Digital Product Passport (DPP) for Material and Product within the Construction Sector

Supervisor: Prof. Adam Glema **Author:** Omar Abuhalaweh

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Abstract:

The digital product passport is an essential tool for the EU's transition to a circular economy, as it provides information on the environmental sustainability of a product. By improving the traceability and transparency of products across the whole value chain, DPP enhances the management and sharing of product data. This is essential for ensuring the long-term use of products, extending their lifespan, and achieving greater circularity. Despite the potential of DPPs to foster circularity, significant gaps exist in the literature, especially within the construction industry.

This thesis sought to fulfil four given research objectives. First, the study explores the benefits of the digital product passport (DPP). Second, the research describes the information that should be included in such passports and the data needed by key stakeholders to maximise the advantages of DPPs. Third, the study reveals which stakeholders in the construction field can benefit from such passports. Finally, this thesis examined the potential of integrating DPPs with BIM. To fulfil these objectives, a mixed-methods approach, including case studies, surveys, and expert interviews, was employed to gather qualitative and quantitative data.

This study reveals several key advantages of DPPs. First, DPPs can help increase traceability of construction materials, a change described as one of the "most important factors in quality control." Second, DPPs can assist with transitioning to a circular economy, promoting the reuse and recycling of materials, and they also contribute to simplifying compliance with environmental regulations, which is especially important in light of the tightening of these rules. Stakeholders such as contractors and facility managers are identified as primary beneficiaries of DPPs. Additionally, several types of data should be included in DPPs, such as environmental information, to maximise their effectiveness.

Finally, the research recommends adapting statutory content in a digital product passport depending on the product category. A balance between protecting the interests of intellectual property rights and maintaining transparency by deciding at what level enough information has been described is essential.

Keywords: Digital product passport, circular economy, traceability, construction products, Building information modelling, Recyclability

Streszczenie

Paszport produktu cyfrowego (DPP) jest kluczowym narzędziem w przejściu UE do gospodarki o obiegu zamkniętym, ponieważ dostarcza informacji o zrównoważeniu środowiskowym produktu. Poprawiając śledzenie i transparentność produktów w całym łańcuchu wartości, DPP wzmacnia zarządzanie i wymianę danych o produktach. Jest to niezbędne do zapewnienia długoterminowego użytkowania produktów, wydłużenia ich żywotności i osiągnięcia większej circularności. Mimo potencjału DPP do wspierania circularności, w literaturze, zwłaszcza w branży budowlanej, istnieją znaczne luki.

Niniejsza praca magisterska miała na celu spełnienie czterech określonych celów badawczych. Po pierwsze, badanie bada korzyści płynące z paszportu produktu cyfrowego (DPP). Po drugie, badania opisują informacje, które powinny być zawarte w takich paszportach, a także dane potrzebne kluczowym interesariuszom, aby maksymalnie wykorzystać zalety DPP. Po trzecie, badanie ujawnia, które grupy interesu w budownictwie mogą skorzystać z takich paszportów. Wreszcie, w pracy magisterskiej zbadano potencjał integracji DPP z BIM. Aby osiągnąć te cele, zastosowano mieszane metody badawcze, w tym studium przypadku, ankiety i wywiady z ekspertami, w celu gromadzenia danych jakościowych i ilościowych.

Badanie ujawnia kilka kluczowych zalet DPP. Po pierwsze, DPP mogą pomóc w zwiększeniu śledzenia materiałów budowlanych, co zostało opisane jako jeden z „najważniejszych czynników kontroli jakości". Po drugie, DPP mogą pomóc w przejściu do gospodarki o obiegu zamkniętym, promując ponowne użycie i recykling materiałów, a także przyczyniają się do uproszczenia przestrzegania przepisów środowiskowych, co ma szczególne znaczenie w świetle zaostrzenia tych przepisów. Jako główni beneficjenci DPP identyfikowani są interesariusze tacy jak wykonawcy i zarządcy obiektów. Dodatkowo, aby zmaksymalizawać ich skuteczność, w DPP powinno się uwzględnić kilka rodzajów danych, takich jak informacje o środowisku.

Na koniec badania zalecają dostosowanie treści ustawowej w paszporcie produktu cyfrowego w zależności od kategorii produktu. Istotna jest równowaga między ochroną interesów praw własności intelektualnej a utrzymaniem przejrzystości poprzez ustalenie, na jakim poziomie opisano wystarczająco dużo informacji.

Słowa Kluczowe:

Paszport produktu cyfrowego, Gospodarka o obiegu zamkniętym, Śledzenie, Produkty budowlane, Modelowanie informacji o budynku, Recykling

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Table of Contents

List of Tables

List of Figure

List of Abbreviations

AI	Artificial Intelligence
API	Application Programming Interface
BIM	Building information Modelling
BREEAM	Building Research Establishment Environmental Assessment Methodology
CDW	Construction and Demolition Waste
CEAP	Circular Economy Action Plan
CE	Circular Economy
CPR	Construction Products Regulation
DOP	Declarations of Performance
DPP	Digital Product Passport
EPD	Environmental Product Declaration
EPR	Extended Producer Responsibility.
ESG	Environmental, Social, and Governance
ESPR	Ecodesign for sustainable products regulation
EC	Europe Commission
EU	European Union
GDPR	General Data Protection Regulation
IEA	International Energy Agency
IoT	Internet of Things
LEED	Leadership in Energy and Environmental Design
QR	Quick Response
SDGs	Sustainable Development Goals
SMEs	Small and Medium-Sized Enterprises
SPI	Sustainable Products Initiative
UNEP	United Nations Environment Programme
WEF	World Economic Forum

1. Introduction

1.1 Background

The construction industry is an essential area for economic growth and global development. Nevertheless, it is a sector with a highly detrimental effect on the environment, and the company makes a significant environmental contribution. One of the significant shortcomings is the culture of consumption and insatiability of resources characteristic of this industry's production processes, raw material extraction, energy-intensive production, material traffic flows on highways, and building construction and installation. A combination of these activities generates extreme emissions and increases the consumption of natural resources and energy, destroying ecosystems and contributing to global warming [UNEP][1]. Construction accounts for 40% of raw material extraction in the world, contributes to one-third of all CO2 emissions, and is responsible for 40% of worldwide solid waste production (Heinrich & Lang, 2019) [57].

Furthermore, the construction industry is also known for its poor waste management techniques that lead to yearly amounts of building and demolition waste being buried in landfills. The problem not only relates to the depletion of natural resources but also to pollution, which tends to increase, as well as other forms of environmental degradation. Sometimes, construction waste is made up of hazardous materials that can be harmful if left uncontrolled and poorly disposed of for humans as well as for the environment [IEA] [2].

These environmental challenges are exacerbated by the linear economic model that prevails in the construction industry. In this model, materials are extracted, processed, used in construction projects, and ultimately disposed of at the end of their life cycle. This linear approach leads to the depletion of finite resources, the generation of waste, and pollution, thereby contributing to the industry's negative environmental footprint. One of the possible alternatives to address environmental problems is the circular economy. It is also designed to decrease waste, increase material and product performance, and promote the use of all recyclable materials and products. The construction industry has the potential to become sustainable by transitioning from a linear economic model to a circular one [3]. There are several signs that the circular economy is becoming increasingly present on the agendas of both industry and policymakers. One of them is, for example, the European Union's newly adopted Circular Economy Action Plan and an expanding portfolio of studies indicating that the circular economy is becoming more relevant for firms (Walden et al., 2021) [58].

A circular economy for construction recognises materials as valuable resources that can be reused, refurbished, or recycled instead of being deemed waste. As a result, construction initiatives emphasise using recycled and renewable materials and re-usable patterns that can be deconstructed and re-constructed over subsequent life cycles (European Commission, 2020) [5]. The practice ensures that the construction industry reduces its impact and reduces the need to utilise new materials during future developments of buildings and infrastructure.

Furthermore, construction under circular economy practices stresses the need to reduce resource utilisation as well as enhance the energy performance of buildings and reduce their carbon footprint. This includes the utilisation of efficient and innovative construction technologies, including prefabrication and modularity, among others, which not only reduce material waste but also help in achieving faster construction project durations and reducing energy utilisation during the construction phase (World Green Building Council, 2021) [59].

Additionally, additional strategies such as design for deconstruction and cradle-to-cradle principles guarantee that the materials are in rotation for as much time as possible, leading to them being maximised for their value and minimising the need for virgin sources.

Nowadays, the construction industry encounters increasing pressure to, as much as possible, enhance its sustainability and transparency. A viable answer to this problem emerged with the advent of digital product passports. The European Commission has suggested implementing "Digital Product Passports (DPPs)," which are a standardised method for collecting and exchanging information on a product throughout its cycle, from raw material acquisition to end-of-life disposition or recycling (European Commission, 2022a) [4] [5].

The proposed revisions to the Construction Products Regulation (CRP) and the Eco-Design for Sustainable Products Regulation (ESPR) evidently indicate a major shift towards a more sustainable and transparent construction industry. The notable provision included in these revisions is the mandatory implementation of construction digital product passports. Under the revised CPR and ESPR, DPPs can play a greater role in achieving results [13]. Both CPR and ESPR will remain important for construction products' regulation. However, CPR is primarily adjusted to individual safety and performance considerations. In comparison, the ESPR contributes to ecological and sustainability considerations, and . DPPs have the potential to make a significant impact under revised CPR and ESPR [13]. It can be concluded that both CPR and ESPR are significant for the regulation of construction products. While the CPR is adjusted to protect individual safety and performance, the ESPR is designed to enhance ecological and sustainable considerations. As a result, the proposed changes aim to close this gap and include sustainable recommendations in the CPR framework [13].

The concept of a digital product passport DPP is a significant milestone in the realisation of the construction industry's aspirations for transparency, traceability, and sustainability. A DPP is a digital platform that consolidates complete detail on a newly developed construction product's life cycle, from the extraction of raw materials to the end of its useful life or recycling (Götz et al., 2022) [18]. The digital passport contains data on the product's composition, environmental and social impact, manufacturing processes, certifications, and performance characteristics. Having so much information readily available for the stakeholders, DPPs can provide good information for decision-making and propel sustainable consumption and production, which is everyone's dream [18].

In addition to transparency, DPPs offer the industry the confidence required to drive the construction supply chain. They invariably drive cooperation, development, and change. The transition of the construction business to a digital format and its endeavours to tackle ecological and social matters. In this scenario, a digital product passport is a key vehicle metric that may be an example of active ownership on the route to a more sustainable and resilient built environment. Moreover, the DPPs help to build transparency and confidence in the construction supply chain, which paves the way for cooperation, development, and change. The transition of the construction business to a digital format and its endeavours to tackle ecological and social matters. In this scenario, a digital product passport is a key vehicle metric that may be an example of active ownership on the route to a more sustainable and resilient built environment (European Commission, 2022a) [4].

1.2 Problem

In the current linear economy of the construction sector, it is difficult to access most of the product's information due to the absence of standardised protocols. A significant amount of data crucial for transitioning to a circular economy is lost at different stages of the supply chain, starting with producers and distributors. Zeiss, Ixmeier, Recker, and Kranz (2021) highlight that by extending product life cycles, digitalization has facilitated changes in business models that enhance product utilisation during the usage phase, leading to waste reduction.

Due to its significant impact on the environment, the construction sector is under increasing pressure to improve sustainability and transparency. According to Heinrich and Lang, a third of all carbon dioxide emissions, 40% of the world's garbage, and 40% of the extracted resources are used by the building industry. It has been suggested to introduce digital product passports for building products to address these issues. These passports would provide an easily accessible system that highlights the capabilities and requirements of a product or material in relation to a circular economy, focusing on resource efficiency, reuse, regeneration, and recycling. These passports should not only serve a sustainable purpose but also provide valuable information to assist the construction industry in optimising material usage during the execution stage and to enhance project management in this sector.

1.3Research Question

The lack of understanding about the product information communicated through DPPs and their important details is provided in the scientific sources about the nature of products' life cycles during the transition stages in a circular economy. These findings may become valuable for companies interested in the implementation of proper digital technologies to collect the information presented in DPPs and meet EU legislation requirements. Additionally, it is not clear who the beneficiaries of DPPs are in the construction field, why the DPP schemes for products and materials have to be established in this sector, and what advantages and benefits are expected.

What is the purpose of implementing the DPP for products and materials in the construction sector and its predicted benefits?

What information should be included in the DPP regarding construction products and materials?

Which stakeholders within the construction sector will derive advantages from the DPP?

What are the benefits of Digital Product Passport For Building Information Modelling?

1.4 Purpose

The aim of this research is to identify the product details to be communicated by DPP and their importance at different life-cycle stages of the construction product, aiming to transition towards a circular economy. The study aims to identify the anticipated benefits of DPPs, the major stakeholders that should engage in DPPs, and the crucial editing patterns of the data assimilated in the DPPs. As a result of a systematic literature review and an empiric study, my research could provide vast information regarding how DPPs make transparency, sustainability, and productivity feasible. Furthermore, the study pursues such alternative goals as discovering that DPPs can be beneficial for construction teams during the project execution phase. Overall, the thesis is supposed to cover the following points:

Purpose and Benefits of DPPs: The research aims to explore the main reasons for the use of DPPs in construction products and materials. Additionally, it is designed to find out what positive outcomes can be expected with the integration of DPPs and how it can enhance the transparency, traceability, and sustainability of the construction supply chain and boost performance and decision-making.

Information Including: Determine the basic information blocks that should be presented in DPPs devoted to construction products and materials. This analysis is based not only on the examination of product specifications but also on a range of parameters, including performance-related aspects, environmental issues, regulatory parameters, and social indicators. Thus, this work should establish the basis for the coverage and integration of the necessary information in DPPs, creating a solid foundation for information management in the field.

The intended scope of the DPP is information related to:

- Sustainable development.
- Closed circuit.
- Value for reuse, regeneration, and recycling.

Stakeholders and Beneficiaries: The study aims to determine the specific construction industry stakeholders who may benefit from the implementation of DPPs. This may include manufacturers, contractors, architects, engineers, regulators, and end-users in the construction industry. Understanding the various needs and views of all these actors will also help to determine how DPPs affect value creation and collaboration across different actors.

Benefits of DPP for Building Information Modelling: The integration of DPP with BIM may bring several advantages, such as enhanced accuracy and completeness of BIM models through detailed product information, improved transparency, and traceability within BIM workflows that make stakeholders able to access trustworthy data about building materials and products. Moreover, a simple and reliable documentation process will reduce the time and effort spent on material selection, specification, and reporting.

1.5 Delimitation

As DPPs are at an early stage of implementation, the scope of this thesis is to understand what product information DPP carries, the role it plays in facilitating the circular economy and sustainability in the construction sector, and which stakeholders will benefit from the Digital Product Passport. To answer research questions and achieve the purpose of this thesis, the insulation material Smart Roof Base, which is produced by KNAUFINSULATION, is taken as a case study.

1.6 Thesis Outlines

The thesis consists of six chapters; Chapter 2 is a comprehensive literature review that provides a broad overview of prior studies on DPPs. This chapter addresses the definition of DPPs, what they are, their benefits, and their importance to the construction industry. Additionally, the type of information needed and the relevant challenges for DPP implementation in the industry are discussed. In addition, this chapter provides insights on the topic of circular economy, specifically definitions and core principles, and demonstrates the applicability of the most important principles to the field of construction. The present chapter also makes references to the unique benefits of the construction of circular economy-based practices as well as the related challenges. Finally, the centrality of data and digitalization for achieving the desired circularity achievements within the construction industry is discussed.

In chapter 3, the methodology used in the study is detailed. It is described which experimental approach is chosen for the research and how it helps answer the research questions of the thesis. Also, a case study for this thesis is chosen and described to show the specific context of the research.

In chapter 4, the primary aim of this chapter is to present the findings and results. The goal is to determine the effectiveness and implications of DPPs in the construction field. This will be achieved by conducting a detailed analysis and explanation of the results obtained, with the aim of answering the research questions.

Chapter 5, This chapter consists of the results and discussions derived from the selected case study. This part also presents the analysis and interpretation of the obtained findings in the context of the case. Thus, this part allows for receiving more valuable information about the practical application and issues concerning DPPs.

To conclude, Chapter 6 represents the logical end of the thesis. In particular, it offers a summary of the research’s findings, the implications of the study, and recommendations for future research.

2. Literature Review

The purpose of conducting a literature review in this study is to examine the existing knowledge about the Digital Product Passport (DPP) in a systematic manner. The main goal is to evaluate research projects related to the DPP and circular economy and gain an understanding of industry professionals' perceptions of these concepts.

This chapter of this thesis consists of two sections: the first covers theories revolving around digital product passports (DPPs) and the second covers the concept of circular economy to understand the idea behind the DPP for construction products.

2.1 Digital Product Passports

This section investigates the definition of the DPP and underlines the significance and advantages of integrating the DPP. Additionally, the data required for a DPP, as well as its implementation challenges, are outlined. Finally, DPP's timelines within the Circular Economy Action Plan are presented.

2.1.1 Definition of Digital Product Passport

According to the European Commission, a DPP is a set of standardised digital information associated with a product that supports its circularity (European Commission, 2021) [5]. DPP is a digital platform that increases transparency, trust, and efficiency in the circular economy by providing reliable product information. (Rezaee et al., 2020) [6]. A digital format is utilised to collect, document, and exchange all relevant data associated with a construction product. (ECTP, 2020) [7]. Based on WEF (2021), the digital product passport (DPP) provides a comprehensive record that ensures transparency and traceability throughout the product's entire lifespan [8]. The DPP would cover a product's origin, composition, and ability to be repaired or disassembled. It would also provide information on how different parts may be recycled or disposed of when their useful lives come to an end (Götz et al., 2022) [18]. According to Construction Products Regulation (CPR) guidance, DPP is defined as a digital file containing information about a construction product throughout its lifecycle, including its technical properties, performance characteristics, environmental impact, and end-of-life options.

A digital product passport, according to the European Parliament (2020), is a tool that provides information on the environmental impact of products throughout their entire lifecycle, aiming to facilitate sustainable consumption and production. Digital Product Passports (DPPs) are a vital tool for achieving these objectives, and they are included in this larger concept. A Digital Product Passport (DPP) is a structured collection of product-specific details, containing a set amount of data and following specific guidelines for data handling and availability. This collection is distinguished by a unique identifier and can be electronically accessed through a data carrier. The main goal of the DPP is to offer information related to sustainability, circularity, and maintaining value for reuse, remanufacturing, and recycling. [9]

DPPs could be a big step forward for more sustainable products and consumption, boosting energy and resource efficiency by enabling new business models based on, e.g., digital data sharing. DPPs could also substantially contribute to the improved security of energy and material supply for a resilient economy (Prof. Dr-Ing. Manfred Fischedick).

2.1.2 Importance and Benefits of Digital Product Passport

According to the European Commission, the Digital Product Passport will “help consumers and businesses make informed choices when purchasing products, facilitate repairs and recycling, and improve transparency about products’ life cycle impacts on the environment.” In other words, the DPP, which some have taken to calling a “digital twin” to the physical products in the EU marketplace, is going to give key stakeholders substantial and immediately accessible knowledge about the products they buy and sell. [10]

The new "Digital Product Passport" aims to provide details regarding the environmental sustainability of products. This data will be easily accessible through scanning a data carrier and will include attributes like durability, reparability, recycled content, and spare parts availability. It aims to help consumers and businesses better inform their decisions when purchasing products, provide repair and recycling support, and increase transparency in relation to environmental impact throughout the life of a product. Additionally, the product passport may help public authorities practice more effective checks and controls. [10]

Additionally, the digital product passport will enable the sharing of key product-related information that is essential for products’ sustainability and circularity, including those specified in Annex III of the ESPR proposal, across all the relevant economic actors. Consequently, to accelerate the transition to a circular economy, boost material and energy efficiency, extend product lifetimes, and optimise product design, manufacturing, use, and end-of-life handling, [11]

A Digital Product Passport also accelerates the circular economy transition and supports multiple circular practices, increased circularity, and holistic CO2 reporting using DPPs (Götz et al., 2022) [18]. By improving product traceability, the passport allows the client to obtain better monitoring to make the best decisions and do more digital circularity practices through this tool. (Adisorn et al., 2021; Götz et al., 2022; Heinrich & Lang, 2019; Walden et al., 2021; Watson et al., 2023) [57].

According to Götz et al. (2022), DPPs have the potential to provide extra layers of reliable product information about recycled content and raw materials, including information on recycling by end consumers; thus, each link in the value network will have more transparency, tracking, and uniformity. DPPs could be able to inform manufacturers on the critical characteristics of secondary materials, such as purity, substances of concern, materials used, additives, fillers, and dyes. Specifically, recycled materials are required to satisfy the same standards as primary production in terms of performance and product safety. [18]

It is necessary to establish well-functioning information flows, including via electronic means and in a machine-readable format, to ensure that coherent and transparent information about construction product performance is available along the supply chain. This will enhance transparency and optimise the efficiency of information transfer. Enabling digital access to comprehensive information about construction products will play a significant role in the overall digitalization of the construction sector, ensuring its suitability for the digital age.

Access to reliable and enduring information will also prevent economic operators and other stakeholders from engaging in non-compliant practices with one another (see Table 1) [12].

Table. 1 Importance and Benefits of Digital Product Passport

Benefits	Description
Enhanced Transparency and Traceability	The provision of accurate and up-to-date information about construction products to stakeholders is facilitated by DPP, thereby enhancing transparency (European Commission,2020) [5]. The documentation of the origin, composition, and characteristics of materials guarantees traceability, enhancing accountability and compliance (BMU, 2023) [20].
Support for Circular Economy	DPPs promote circular economy principles by providing data on product reuse, remanufacturing, and recycling, thus reducing waste, and promoting resource efficiency (Ellen MacArthur Foundation) [3]. A Digital Product Passport accelerates the transition to a circular economy by enabling a variety of circular practices (Götz et al., 2022) [18].
Sustainability and Circularity	It enables the tracking of materials throughout their lifecycle, promoting reuse, recycling, and responsible disposal (Li et al., 2020). DPP promotes sustainable practices by facilitating the selection of environmentally friendly materials and supporting circular economy principles (European Commission, 2020) [5].
Efficient Product Lifecycle Management	They provide guidance on proper use, maintenance, and disposal of materials, extending the lifespan of buildings and infrastructure (Li et al., 2020). DPPs include information on the lifecycle stages of construction products, aiding in maintenance planning and lifecycle management (European Commission, 2020) [5].
Consumer Empowerment	DPPs empower consumers to make informed purchasing decisions by providing access to detailed product information, including environmental impact and sustainability credentials. principles (European Commission) [10], (Götz et al., 2022) [18].
Compliance with Regulations	DPPs aid in compliance with regulatory requirements by documenting certifications, standards adherence, and regulatory specifications (European Commission, 2020) [5]. They ensure that construction products meet legal and industry standards, reducing the risk of non-compliance penalties and project delays (BMU, 2023) [20].

2.1.3 Data requirements for a Digital Product Passport

The new “Digital Product Passport” will provide information about products’ environmental sustainability. A data carrier scan allows users to find all information quickly and easily about the durability of their product, its reparability, the recycled materials used, and whether spare parts are available. This initiative seeks to empower consumers and businesses to make well-informed purchasing choices and streamline the repair and recycling processes. It will also help bring more transparency to the true environmental impact of a product from creation to disposal. The product passport will also make it easier for public administrations to perform better checks and controls. (European Commission, ESPR) [13]

In order for a construction product covered by a harmonised technical specification to be placed on the market, the manufacturer is obliged to draw up a declaration of performance for such a product. The responsibility of ensuring that the product meets the specified performance standards lies with the manufacturer. However, certain products, such as those that are manufactured or produced on a one-off basis, may be exempt from this obligation. Furthermore, the manufacturer must draw up a declaration of performance for any construction product before placing it on the market. The manufacturer assumes responsibility for the conformity of the product to its declared performance. Certain exemptions from this obligation are provided. (European Parliament, CPR) [14]

Based on the above, the most important difference between the DPP based on the ESPR and the DPP based on the CPR lies in their scope. The DPP based on the ESPR is concentrated on ensuring the environmental performance of a product and highlights its influence on sustainability and the environmental consequences of producing this product in all phases of lifecycle assessment. On the other hand, the DPP, according to the CPR, tends to be more extensive in its essence and is dedicated to the environmental and technical characteristics of a construction product to provide the industry with the relevant information and the correlation with the regulatory framework. [17]

DPPs can be a leading data carrier for a product or material. Their listing offers both master data, like the product name, manufacturer, composition, substances of concern, toxicity, and usage, and new data, including usage, modification, maintenance, and wear and tear. DPPs can make information monitoring and management based on the composition and lifecycle of a product or material. The DPPs may become the main information carrier for a product or material, containing master data on the product, manufacturer, composition, substances of concern, toxicity, and sourcing, as well as new data on use, modification, maintenance, and wear and tear. They make it possible to monitor and record information about the composition and life cycle of a product or material. Ideally, such digital data management might enable close to real-time environmental impact monitoring. [18]

In this literature, four crucial pieces of information the Digital Product Passport should include are discussed to help achieve the European Commission and European Parliament's objective of accelerating the transition to a circular economy. Manufacturing and technical data, usage data, end-of-life data, and life cycle data.

Manufacturing and Technical data, manufacturers and suppliers are, generally, the main actors to provide the specific product information. This should contain the product’s composition, the materials, and the weights used in each component. Additionally, a technical data sheet should be provided [15].

A digital product passport should include key data and information, such as when and where the product was installed and how many hours it has been running. Has it operated at its highest capacity continuously or at different levels? Having knowledge about the running hours could, in combination with the estimated average product lifetime, provide an indicator of the remaining lifetime of a product. [16]

Therefore, manufacturers will undoubtedly still be the main sources of product information [19]. However, additional transaction costs, such as those related to obtaining more information (which might also involve requesting information from suppliers), must be minimized. It is nonetheless note-worthy that as people become more familiar with this process over time, the longer-term administrative costs are also likely to decrease [15]. The performance and durability of a product and its components should be noted. With information on component dismantling and changing, people can improve the life expectancy of a product and begin to imagine what the product will be like when it functions as optimally as possible. For instance, in the case of DPP, the batch number is useful because it makes all products that were produced at the same time traceable under identical conditions. [17]

Usage data is also considered data that can be included in a digital product passport. During the use of complex products, all changes should be recorded. This includes documentation of parts that have been replaced or repaired. The organisation or individual that makes use of adjustments is responsible for updating the DPP. Frequent product-species damages and damages to components, particularly those that are critical for health and environmental safety, should be recorded to ensure proper handling and enable optimisation of the product. Users will ideally show how they intend to dispose of the product at the end of its life. This in turn helps plan CE better and properly points out waste collection campaigns.[17]

End-of-Life Data: The DPP should include documentation on collection, sorting, and treatment during the End-of-Life (EoL) phase. In combination with user input, this data can help improve the environmental performance of a product. The recording of the achieved collection fraction of the product can be compared with the sales volume. This yields alternative means of calculating what the likely market penetration is and obviates the need to make further purchase decisions based on individual product costs. In addition, information on the recycling method used should be noted, and the output streams of the process should be recorded. This information can be fed back to product manufacturers and aid them when designing (or redesigning) products for increased circularity.[17]

Life-cycle data and sales volume can be used to predict how future waste may change with the flow of time and how many resources might yet be recycled. This can conduct economic and CE forecasts. But these are uncertain figures that vary according to different elements such as the service life of a product, user behaviour, and recycling opportunity [17]. In addition, the DPP should provide step-by-step descriptions as well as storage and application techniques, which themselves try to help users avoid possible negative health or environmental results. The DPP is also a powerful tool for implementing the Sustainable Development Goals (SDGs) [60]. Thus, environmental information about a product should be made public, which helps consumers decide how helpful their purchases are [61]. Additionally, the way to carry out a social lifecycle assessment (SLCA) is also given consideration, along with a rather general description of the results it might yield [62].

2.1.4 Challenges in The Implementation of a Digital Product Passport

According to Götz et al. (2022), one of the main challenges of constructing a digital product passport (DPP) is how much information it should include over the life of a product, including repairs and usage. Should all this data be integrated within a single DPP? It may be impossible. In fact, due to system complexity, this kind of depth of detail for every conceivable type of product might be difficult to manage practically [18]. The practical problems that arise from such a comprehensive approach are typified by how to store this mountain of data for DPPs. It is the majority view in most industries that a newly built, holistic, single database ought not be created because a focused, decentralised approach makes sense. Therefore, we need to define at least the main objectives of DPPs at an early stage and make them explicit. An accompanying roadmap will also be required to move from a simple, minimum viable product to a more complex instrument. [18]

Another potential challenge might be the difficulty of accessing data for the DPP database, which will be vital for policymakers and consultants alike, as well as for researchers who provide backup assistance in policy making. Additionally, practical data issues particularly concern what data will be available in the DDP package and how it will be kept current after the product has been put on the market. Data can be updated during use but also after, right up until the final EOL. [19] When a certain product group's market size is large and there are numerous pieces of information, if we only use the Digital Product Passport (DPP) database, it will not be sufficient, and many researchers in the field might have difficulties evaluating. In this case, therefore, evaluation experts would demand a database that does specific searches and retrieves processed or summarised information, such as the average size or nominal power of products. That would enable them to make even better evaluations [19].

Götz et al. (2022) also noted that the transparency of information is also an important issue. This is because business confidentiality must be guaranteed through different levels of access rights. The main concern here is at what point the criteria for DPP should be applied. Some business stakeholders said that recyclers and consumers should be able to decide what information they ‘need to know and how commercially sensitive information can be protected. However, such arguments should not be accepted as a reason to keep quiet about some things, such as hazardous substances in a product. If a ‘need to know’ principle would imply non-transparency as the default rather than transparency, this could be incompatible with genuine circular economy targets. [18]

From the viewpoint of certain companies, DPPs could be a very difficult thing for complex products (containing thousands of mutually independent single sub-systems), depending on the DPP’s design and implementation. Currently, some industrial sectors believe it would be impossible to implement DPPs in isolation; they say that a complete DPP ecosystem is needed if we are to move towards an ecological system at all levels of production. Which, in turn, requires governance mechanisms, particularly in how to measure, validate, and share data points. Another problem is that sustainability information is regulated by different policy instruments. To address social information, legislation must define the nature and form of a DPP.Therefore, it is important to see what the EC has in mind when electrifying extended social and environmental information via DPP. [18]

The implementation of a Digital Product Passport (DPP) requires the participation of many kinds of domain experts: product owners, material specialists, and ESG (environmental, social, and governance) managers to create a comprehensive DPP. Gradually larger numbers of people are being asked to help prepare a DPP, all without having spent any intensive study period or apprenticeship in user requirements! However, the young battery manufacturing industry considers it relatively unimportant, but sectors such as waste management and building and construction might have some real difficulty because they lack experts by occupation [20].

Other challenges associated with DPP implementation include a skill shortage among domain and IT experts. Since a Digital Product Passport (DPP) is primarily an IT project, it cannot function without digital professionals, including database specialists, data scientists, developers, and system administrators. For example, software and other companies have virtually no shortages, and even online businesses or IT consulting firms are likely to have enough specialists. The situation is very different in the building and construction industries, especially in waste. Since the implementation of the DPP relies on existing domain experts, the scarcity of programmers is a critical issue [20]. In addition, the cost of implementation and maintenance is a challenge. Implementing a DPP in an organisation presents a challenge due to the costs to be incurred in terms of investments and expenses, as discussed above. Accuracy and reliability of the data included in DPPs are also challenges, specifically in environmental impact assessments and lifecycle data, especially in terms of data quality and reliability. [20]

2.1.5 Stakeholder Engaged in Digital Product Passport

According to Götz et al. (2022), digital product passports (DPPs) can be utilised in different industries, from drift battery manufacturing to textiles, furniture, electronics, and building materials. This idea takes after concepts like Material Passports and Building Information Modelling (BIM), as well as initiatives in the automotive sector such as Catena-X [18]. Plociennik et al. (2022b) simplified the potential users of DPP into two main groups: those directly involved with materials and those focused on strategy (see Figure 1). They made this division based on how people interact with the DPP, the kind of information they provide, and what they aim to achieve with it [17].

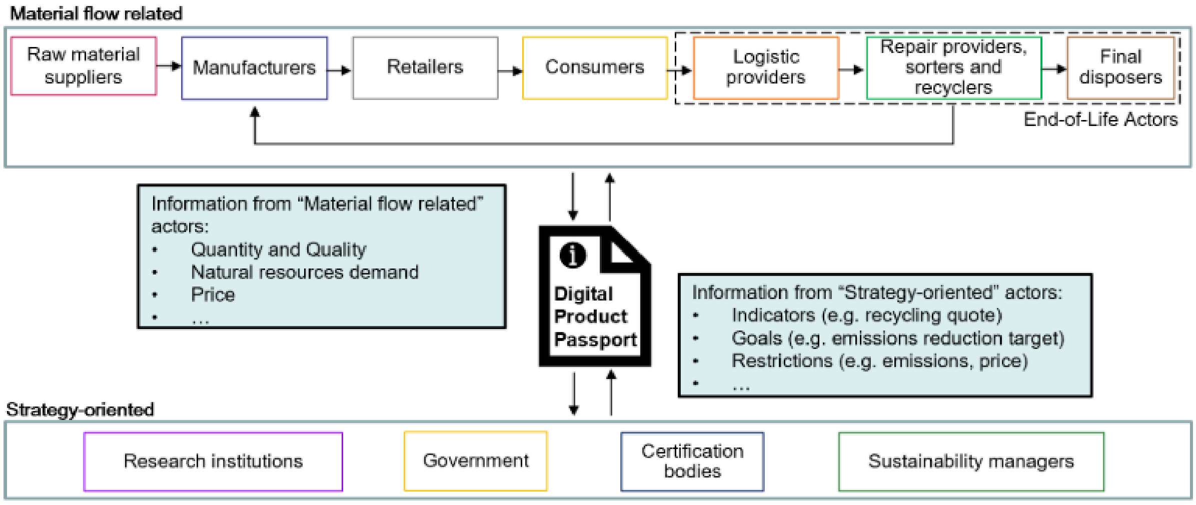

Figure 1: Potential users of the DPP (based on [17])

Material flow-related actors, like industries, retailers, and recyclers, deal directly with materials and the processes involved in handling them. They provide information such as the quantity, quality, and composition of a product or material, how much of a product or material there is, what it's made of, and how much energy, water, and raw materials are needed to make it. Strategy-oriented actors, such as government agencies, research institutions, certification bodies, and sustainability managers, use the DPP to access material flow information. They do this to set clearer goals, create strategies, and implement actions. They also use the data to calculate performance indicators [17]. This may result in increased resource efficiency, a decrease in the amount of resources required, or even their sufficiency, the removal of pointless procedures, or a decrease in the consumption of primary resources.

When it comes to information needs, Placiennik et al. found that manufacturers and end-of-life actors are usually ready to share any information corresponding to demands made of them (see Figure 2). However, there are exceptions: End-of-life actors demand to know what components in the product are hazardous substances; not all manufacturers will provide this information. This shows how interests differ and there is potential conflict.

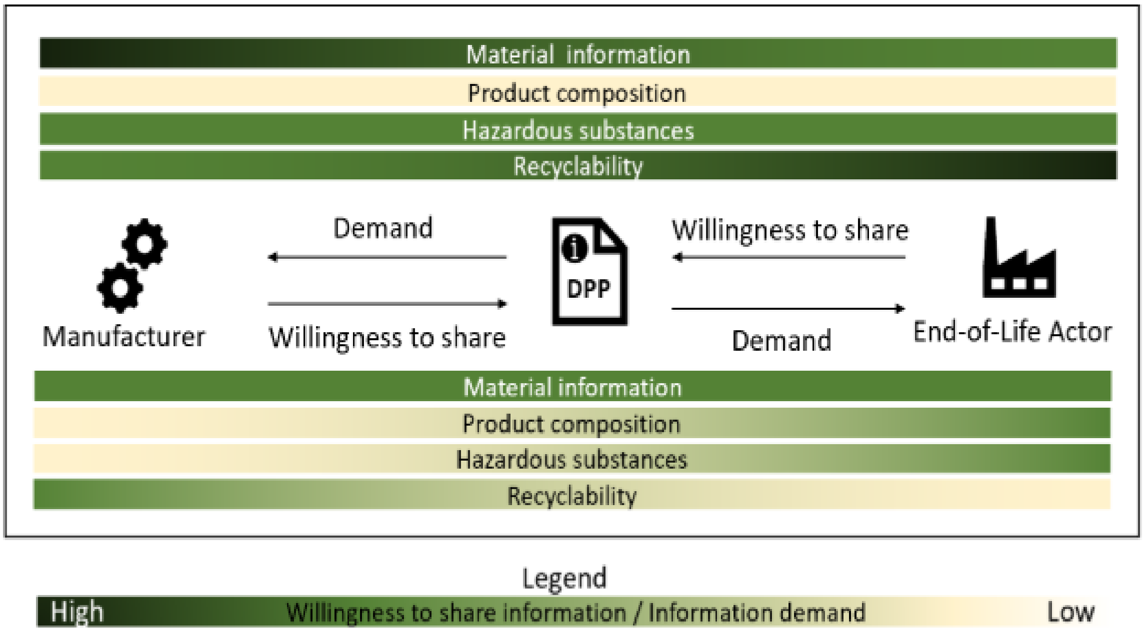

Figure 2: Mutual information requirements of DPP based on [17].

2.1.6 Timelines of DPP According to Circular Economy Action Plan

The discussion on the Digital Product Passport (DPP) was started in 2014 by the European Resource Efficiency Platform, with an emphasis on the recycling of materials back into the production processes [18]. From there, issues of the circular economy and sustainability took centre stage in the legislative agenda. A huge shift in the product-related policies of the EU was brought in with The European Green Deal in 2019, in which the DPP was announced as a game-changer tool to enhance circularity [18]. This, however, still faces several challenges to be addressed at various stages of development, especially those related to the scope and data of the technology (Wbcsd2, 2023) [53].

The potential spread of DPP among different sectors is likely to take time as the European Commission is working on the design of DPP for distinct groups of products. At the same time, rapid implementation, and the early introduction of transparency through DPP will allow for the decoupling of economic progress from material creation, waste, and carbon pollution. It could bring a real change to the world and to human beings.

Other products expected to benefit from the DPP include industrial and electric vehicle batteries, envisaged under the first category among at least 30 different product categories that the DPP is expected to serve (Inriver, 2023) [54]. Even if set for mandatory compliance in 2026, most of the industrial entities are already taking respective measures to put themselves in order with the provision of those requirements, as, for example, the proof-by-concept presented at the Economic Forum in Davos (Umicore, 2023; Inriver, 2023) [54]. [56]. Developing and implementing the DPP would require a working-together approach among the manufacturers, consumers, and regulators among the stakeholders; these could be some of the factors contributing to the timeliness of the project (Wbcsd1, 2023) [55].

The Circular Economy Action Plan does not provide accurate timelines for DPP implementation; however, the European Commission indicates that the adopted DPPs should be spread in various productions and services [5]. The European Commission is planning for the first regulation to govern product groups to go into effect in either 2026 or 2027 (see Figure 3) [5].

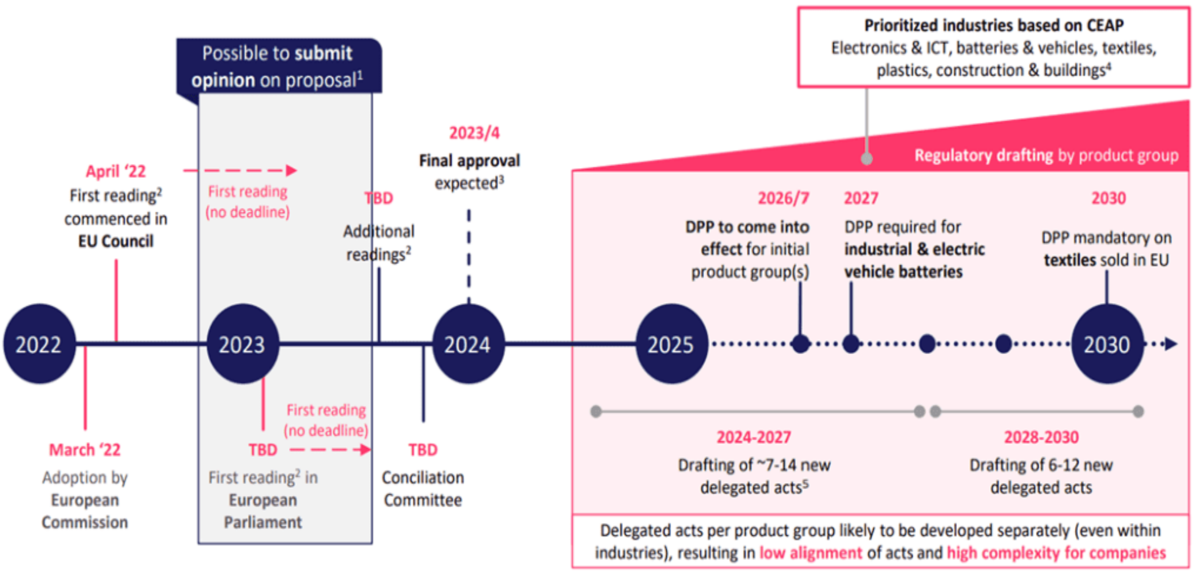

Figure 3: Timelines of Digital Product Passport [64]

2.2 Circular Economy in the Construction Industry

This section of this thesis describes the basic concept of the circular economy. It looks at the framework and its principles to understand how they relate to the thesis. Then, it discusses the benefits of the circular economy in the construction industry. It also provides an overview of challenges in the construction industry, highlights the importance of data for achieving circularity, and emphasises the need for digital technologies to boost the circular economy.

2.2.1 The Concept of Circular Economy

The concept of circular economy has gained attention since the late 1970s (EMF, 2013b) [22]. Andersen (2007), Ghisellini et al. (2016), Su et al. (2013), and Pearce and Turner (1989), among other authors, attribute the introduction of the concept of circular economy (Geissdoerfer et al. (2017)) [24]. They suggested that natural resources determine the level of economic development as they are a source of materials for production and consumption that serve as a sink for waste products. They highlighted the linear and open-ended nature of contemporary economic systems. This idea draws from Boulding's (1966) work, which portrayed the Earth as a closed and circular system with limited capacity for waste assimilation. Boulding suggested that the economy and the environment should exist in equilibrium (Geissdoerfer et al. (2017)) [24].

Stahel and Ready (1976) introduced the so-called circular economy aspects, more specifically in the realm of industrial economics [24]. Their suggested concept of a loop economy established a few related strategies: waste prevention, regional job creation, resource efficiency, and the dematerialization of industries. Simultaneously, Stahel (1982) also pointed out selling utilisation instead of ownership of goods as the main idea behind sustainable business models for a loop economy. Industries could be able to make a detrimental profit without avoiding the cost and risk of externalisation attributable to waste. [24] According to Geissdoerfer et al. (2017), contemporary circular economy, as it is understood and finds its useful applications in economic institutions and industrial activities, has transformed to include new content that arises out of various systems that are all structured around the principle of closed loops [24].

The circular economy, based on the European Parliament, is a way of doing things that focuses on sharing, reusing, fixing, and recycling stuff to make it last longer. It’s all about using things wisely to give them a longer life [21]. Research by Geissdoerfer et al. (2017) defines a circular economy based on three fundamental principles: first, design for durability and recyclability, i.e., promoting a long-term service life of products and their ability to be dismantled; second, resource circulation, including reuse, resource recovery, and recycling; and third, business model innovation, encouraging new ways of delivering value through product-as-a-service, sharing platforms, and re-manufacturing. [24] The Circular Economy, as defined by the Circular Economy Action Plan of the European Commission, is a “comprehensive strategy of production, consumption, and disposal, shifting from the current linear model, in which we extract resources, produce goods, and use and throw away the leftovers, to a regenerative model where we keep resources in use for as long as possible. [5]

According to the Ellen MacArthur Foundation (2013), a circular economy is an industrial system that's intentionally designed to restore or regenerate resources. Instead of thinking about products reaching the end of their lives, it focuses on restoring them. It also promotes using renewable energy, avoiding toxic chemicals that make reuse difficult, and designing materials, products, and systems to minimise waste [22]. The circular economy should centre on regenerating purposefully (Ellen MacArthur Foundation, 2019). It is how materials, energy, humans, and data can effectively move and operate, allowing us to restore our natural and social capital. It seeks to use less energy to produce every product and transition more to renewable energy. Everything within the economy is something we can reclaim; essentially, the circular economy values everything from the industry [23].

The concept of the circular economy isn't only about making and using stuff. It's been invented based on the study of how things work in nature, and in nature, things are complicated and work together. It is like looking at how nature operates if nothing is isolated. All are connected, and feedback loops and interactions will continue indefinitely. A lesson from nature is that we should manage things as a whole system instead of only the components. The point is to take a holistic approach and ensure that we rebuild resources so that we can generate long-lasting benefits. [23] In the circular economy, we must manage two kinds of materials that flow. One type is biologically flowing materials, which are things that we are supposed to return to the environment healthily to aid nature. The excess material flow is a technological process whereby materials can be repackaged with the same quality and do no harm to the environment [23].

A distinction is made in the concept of circular economy between material consumption and the use of materials. For instance, with consumption, it is certain that something like food and drink are altered in a way that can never go back to normal again—while still serving their original purpose, neither they nor their crop leaves could be employed after this period has passed. In a linear system, materials like those used for single-use packaging, fast fashion, and semi-durables also show how, once spent, they become waste [23]. In the circular economy, the aim is to enable a "functional service" model for technical materials (Cradle to Cradle Products Innovation Institute). In other words, manufacturers or retailers would retain possession of their goods and/or establish effective take-back systems. They would also function as service providers who sold the use or function of products rather than their value or consumption [23]. This change has important implications for how businesses create value in new ways.

Innovator and industrial analyst Walter Stahel explains it like this: The linear model turned services into products that can be sold, but this throughput approach is a wasteful one. In the past, product reuse and longevity were efforts often made because people could not afford more or simply because resources were not growing on trees. Needless to say, such choices were not always associated with high-quality products. However, in today's reality, reusing products is definitely a sign of resourcefulness and good business manners. In fact, the term circular economy is a comprehensive vision undoubtedly [23].

2.2.2 Core Principles of Circular Economy

The core principles of the circular economy are rooted in sustainable resource management and aim to minimise waste while maximising the value of resources. Kirchherr et al. (2017) distinguish in their review two core principles of the circular economy. Those relating to the R frameworks and the systems perspective. The first core principle of the circular economy is enshrined in the R-framework, which acts as a compass for the guidelines in systematic circular thinking. Three of the leading frameworks exist since no internationally accepted framework exists, namely the 3R-, 4R-, and 9R-frameworks. The 3R framework has the original R, that is, the founding core principle, Reduce, Reuse, and Recycle. [25]

The 4R-framework adds Recover to this list, which is integral to the Waste Framework Directive of the EU (European Commission, 2008). The most comprehensive framework, the 9R-framework, incorporates Refuse, Rethink, Repair, Refurbish, Remanufacture, and Repurpose. Furthermore, a hierarchy strategy is associated with the first core principle, where the 9R-circular strategies are ranked based on priority, from higher circularity (low R-number) to lower circularity (high R-number) (Kirchherr et al., 2017; Potting et al., 2017). Thus, a strategy with a lower number is preferred, as it provides greater circular benefits by requiring fewer resources for producing new materials (see Figure 4). The concept behind circular strategies R0-R2 revolves around smart product use and manufacture, R3-R7 involve extending the lifespan of products and their parts, while R8-R9 involve the useful application of materials (Potting et al., 2017).[25]

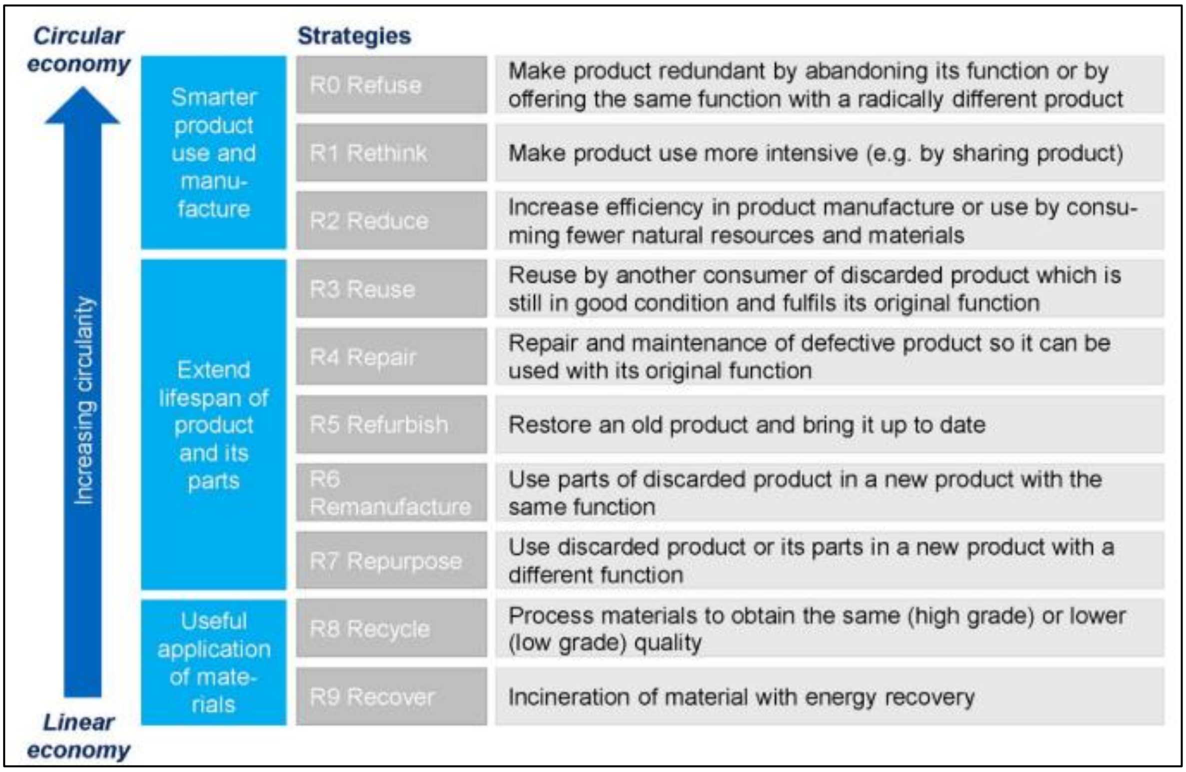

Figure 4. The 9R-framework (adapted from Potting et al., 2017).[25]

The second core principle is the necessity of systemic change because the transition to a circular economy is possible only when the actors at three levels, micro, meso, and macro, act. What is more, each of the levels requires a change for the transition to take place. Specifically, at the micro-level, it is the companies, consumers, and that product level that have to change. The companies and industrial networks that have to change are at the meso-level. At the macro-level, the policies at the national or regional levels, including those related to adjusting the structure of the entire model, have to change.[25]

2.2.3 Benefits of Circular Economy in Construction

Currently, the construction sector operates in the traditional linear economy model and is profoundly unsustainable (Mangialardo & Micelli, 2018). Buildings account for 40% of all waste generated (by volume), excluding major mineral use, account for about 40% of all material resource use (by volume), and are responsible for 33% of all human-induced emissions (United Nations Environment Programme, 2012; World Resources Institute, 2016) [26].

Furthermore, an enormous proportion of all material ever extracted throughout human history is locked up within the built environment (Sanchez & Haas 2018a). Therefore, it must be tended to happen that as needs for materials in the future cannot be all met by nature, a large number of buildings will become temporary material stores [26]. If non-renewable resources are still used wastefully, as at present, then it is highly likely that natural resources will be seriously damaged (Hossain & Ng 2018). As a result, by 2050, the European Union wants all buildings to have zero emissions (European Commission, 2019b) [26].

The circular economy (CE) concept presents a potential alternative to the current “take-make-use-dispose” linear economy. CE is a restorative as well as regenerative system that seeks to diminish the consumption of natural resources along with their wastes and emissions by way of performing several key tactics: narrowing within the efficiency of resource consumption, slowing (temporally extended use), and closing material loops (Reike, Vermeulen, & Witjes, 2018). The strategies of reuse, repair, refurbishment, recycling, and recovery help to operationalize the concept of circular economy (Ellen MacArthur Foundation, World Economic Forum, & The Boston Consulting Group, 2016). [26]. There has been an increasing amount of research in the last two decades circulating around the environmental and economic effects of the construction and demolition sectors. The most common trend has been the production and disposal of waste materials [26]. Core to the operations of the circular economy Source is the immediate minimization of waste disposal in landfills by strategizing alternative uses for discarded items [26]. The CE of construction waste is a 4R solution focusing on reduce, reuse, recycle, and recover operations of raw materials [27]. By increasing the use of reuse, recycling, and recovery methods, the acquisition of raw materials slows down or becomes stagnant. This not only brings economic benefits but also decreases the amount of greenhouse gas emissions produced during procurement and supply chain activities.

The application of more reuse, recycling, and recovery techniques contributes to the slowing down or even stagnation of raw materials. As a result, much fewer greenhouse gas emissions are created during procurement and supply chains. The reduction of waste operations is also advantageous, for it helps reduce the volume of waste produced and lessens various negative impacts of waste generation on environmental processes. [27].

A SUN Institute-sponsored report found that by 2030, a circular economy could reduce the consumption of primary materials by 32% compared to the current linear economy, and by 2050, by 53% [28]. The report also established that a circular economy would increase the productivity of primary resources in Europe and around the world and reduce the use of raw materials [29].

Resource efficiency and sustainability can also be achieved by reducing the demand for primary raw materials in the construction industry, which can be achieved by a system of the circular economy that ensures that products last longer and optimise reuse [28]. The circular system also ensures that nutrients re-enter the biosphere in a safe manner, meaning decomposition for the formation of new raw materials that can be used in the next cycle. More value is also generated by the circular economy since it recycles waste products and uses them again as raw materials in another product [30]. In Europe, for instance, initiatives in the built environment would save 600 million primary resource inputs in a year by 2030. In the long run, there will be fewer primary construction resources imported to be used and more natural resources to be used [30].

Moreover, the research provides evidence that the use of renewable materials can promote proper profits for construction companies [28]. Due to the more efficient use of raw materials, the reduction of waste, and the possibility to recycle the materials that have already been used, small and medium-sized companies in the construction industry can reduce their expenditures, which will naturally allow them to earn more. The need to adhere to the principles of the principles of the circular economy creates new opportunities, improves the competitive position of companies, and provides resistance to multiple strategic threats. [31], The construction industry encourages innovation, the opening of additional sources of income, and the elaboration of long-term relationships in the form of massive contracts. This approach enhances customer focus, makes the management of internal resources more productive, and collects partners along the supply chain that are mutually beneficial. What it means to use circular economy principles is that the entire value circulation in any type of business or industry creates additional economic value. In this respect, this overall approach reduces construction spending and creates additional sources of income for the construction firms [30].

The circular economy has the potential to make our environment better. The benefits would include such factors as controlling water and air pollution [28], controlling climate change, and helping in the management of urbanisation, leading to the more efficient utilisation of land. Of course, it could be pointed out that the impact of such results may also reflect on the construction industry because of its importance. Reducing carbon emissions, therefore, becomes a key goal of circular economy practices since the construction sector is one of the main carbon-emission areas, thereby creating huge pressure on land and water resources. Furthermore, stopping organic waste from going to landfills could avert 7.4 million tonnes of greenhouse gas emissions. Only in Europe could the carbon dioxide emissions be reduced by 48% from strategies on circular economy by 2030 and 83% by the year 2050. This would be significant in respect to landfills because they take up space that could otherwise be used for further future construction development [28].

The circular economy also highlights the necessity of better use of organic waste to enrich the soil, reducing the need for chemical fertilizers. It helps in the regeneration of soil health and reduces chemical pollution. Much more ambitious targets for the recycling of municipal and packaging waste could be set and be coupled with a reduction target for the use of landfills, which could achieve a saving of around one million tonnes of carbon dioxide emissions [32].

By reducing the amount of waste sent to landfills, we free up more land for building and development. With circular economy practices, the aim is to send only 10% of the waste we produce, including waste from construction sites to the landfill [32]. As a result, a circular economy could cut the greenhouse gases emitted by the construction business. It makes sense because using circular materials allows us to use them for longer. Furthermore, by embracing circular economy principles, we can also decrease the environmental damage mining causes to raw materials used in construction. At the same time, we may continue to have access to well-sourced construction materials that don't hurt the environment [30].

Incorporating eco-design, recycling, and other solutions will promote sustainable consumer behaviour as well as create conditions for the improvement of human health and safety in our built environment [33]. The European Commission's impact assessment indicates that adopting circular economy principles could result in an increase in direct job opportunities and could lead to the creation of up to 178,000 new direct jobs by 2030 [34]. By supporting a major employment sector, the circular economy will create more quality jobs, which means better livelihoods in place. The promotion of circular value chains has the potential to greatly improve social sustainability [29]. The European Commission argued that estimates for the United Kingdom suggested that around 500,000 jobs could be created in a circular economy [34]. Finally, the development of circular economy practices supports industrialization; currently, this is regarded as a significant measure of creating prosperity.

Social innovation associated with eco-design, recycling, and other developments can result in more sustainable consumer behaviour while contributing to improving human health and safety in the built environment. [33] The European Commission revealed that, according to the European Commission's impact assessment on a legislative proposal on waste, the adoption of a circular economy could create up to 178,000 new direct jobs by 2030 [34]. . The construction industry is a huge employer of labour. Where circular economy principles are deployed, the construction industry will create more decent jobs that could result in livelihood enhancement. The development of circular value chains might have significantly greater potential for social sustainability [29]. The European Commission argued that estimates for the United Kingdom suggested that around 500,000 jobs could be created in a circular economy [34]. It has been deduced that the development of a circular economy is an important measure to promote industrialization [35]. The deployment of circular economy in the construction process will solve the environmental problems that were generated by waste. As the world's population increases, there will be greater demand for affordable housing; therefore, a notable reduction of the negative environmental pressure our society faces nowadays could be achieved through the adoption of the adoption of circular economy practices in the construction sector [30].

2.2.4 Challenges in Implementing Circular Economy in Construction

Based on a comprehensive literature review, Charef et al. classified circular economy barriers in construction as organisational, economical, technical, social, political, and environmental barriers. [38]. Wuni described 11 categories of circular economy barriers in construction: cultural, market, knowledge, financial, management, regulatory, technological, supply chain, stakeholder, technical, and organisational barriers [39]. Osei-Tutu et al. classified circular economy barriers in construction into six groups: cultural, social, environmental, economic, technical, and technological barriers. It is necessary to mention that technological or technical barriers or challenges to the circular economy in construction are among the regular types of classifications in various studies [40]. According to Bressanelli et al. [41] and Elghaish et al. [42], both technological and other barriers to trade can be solved in principle via developed digital technologies [43].

The construction industry is known for having many different stakeholders, each with distinct priorities. Achieving circularity requires collaboration across these fragmented value chains. However, the building sector has challenges related to the lack of communication between actors and a broad short- and long-term vision of the impacts of the sector's activities throughout and beyond the life cycle of its projects. In addition, given the relatively long lifespan of projects, the complexity of the fleet, and the number of stakeholders involved, it can be challenging to assign responsibilities to stakeholders at a specific stage of the entire life cycle of projects, buildings, and/or products. [36] Technological factors can play an essential role in the lack of tools and digital logistics systems; in addition, the sector must face resistance to change that is rooted in certain actors; and social and cultural challenges are essentially linked to the lack of interest, knowledge, and/or commitment to applying CE strategies. [36]

According to Adams et al. (2017), the lack of incentive to design end-of-life products was the biggest challenge, regardless of company size or experience. Producer responsibility was seen as important by contractors and demolition contractors, but least important by manufacturers.[37] Limited awareness, interest, and knowledge are also identified as significant challenges. Medium- and large-sized companies believed that the lack of knowledge was a greater challenge than smaller companies, although companies of all sizes believed that an awareness campaign would be an important enabler. [37] The lack of end-of-life considerations in building commissioning, design, and construction is defined as a significant challenge. Uncertainty about long-term user needs and adaptability were key issues. Additionally, for the recovery of materials and products, it was found that the lack of market mechanisms to aid recovery was one of the top challenges for implementing CE in the construction sector. Finally, one of the major challenges with embracing circularity in the built environment is that its financial viability remains uncertain. In the opinion of almost all stakeholders, having a clear business case is vital to going along with circular practices. Using circular economy methods in construction may involve stepping up outlays and can mean increased initial costs over traditional linear methods [37].

However, to fully enter the circular economy, construction has to introduce new technologies, processes, and skills. Now, construction is lagging behind severely in technology and skills. For instance, many companies have no clue how to apply the new and innovative digital circular solutions, such as breakthroughs in identifying and tracking materials (Finkbeiner et al., 2018) [63].

2.2.5 Data and Digitalization for Circularity

Data and digitalization have been critical catalysts for circularity in various industries. including those in the built environment. In several papers, including that of (Mangano, G., Pampinella, 2020), data, a data-driven strategy, and digital technologies are emphasised as essential for circularity [44]. Data is acknowledged as the “catalyst that enables the transition. towards a circular economy” (Circular Economy Action Plan, 2020) [5]. Moreover, it is noted that digitalization is essential in supporting any other tool to help promote the circular economy. Digitalization is an important tool to get us to a circular economy. This is because It gives the information needed to keep resources in loops—for instance, where the resources are located, their condition, and their availability. It reduces the material's circular loops; that is that it enables reusing and recycling to be done more effectively. Additionally, digitalization reduces waste, prolongs the life cycle of products, reduces transaction costs, and boosts the efficiency of business processes. (Antikainen et al., 2018) [45].

However, data discrepancies represent a current challenge for the transition to a circular economy. In this case, data discrepancies imply any inconsistencies and missing points that prevent the seamless transition to a circular economy model (Rajput & Singh, 2019) [46]. It is difficult for the parties to track and trace materials and products through the entire lifecycle. Such tracking and tracing are crucial for proper resource allocation and the reduction of potential waste. For example, when I have no information about the product's origin, composition, and possible approaches to the end of their life span, I am less likely to be able to recycle them properly or sustainably dispose of them. Meanwhile, the data may be inconsistent, not only between consumers and producers. In this case, the end of the product lifecycle may lack quality information due to the previous party’s devaluation of the necessity to provide it. Therefore, addressing data discrepancies is essential for unlocking the full potential of the economy and achieving its sustainability goals (Rajput & Singh, 2019) [46].

The data that relates to circularity is various and can provide different actors and industries. with information about material flows, product lifetimes, and associated value and environmental impacts (Luoma et al., 2022a) [47]. Moreover, this data can be utilised to optimise the environmental performance of value chains. Nevertheless, to make more use of circularity, and to manage it more effectively, it requires appropriate information and technological systems. (Luoma et al., 2022a) [47], where digital technologies are considered as essential for this purpose. Through the ability to monitor and optimise the product performances (Rusch et al., 2022) [48], for example, digital technologies serve as the link between data and digitalization, turning theoretical circular economy principles into workable and practical solutions (Chauhan et al., 2022) [49]. The internet of things (IoT), big data, Artificial intelligence (AI) and blockchain are the four digital technology categories that are listed in the CEAP as supporting a circular economy (European Commission, 2020) [6].

Integrating digital technologies throughout the supply and value chains involves the tracking of and tracing of materials and products (Hedberg & Šipka, 2021) [50]. These technologies can address key operational barriers across the value chains (Kristoffersen et al., 2021) [51]. And are expected to pave the way for new innovative business models (Chauhan et al., 2022) [49]. It was expected that these digital technologies could help enhance the design of products. and manufacturing processes, the usage of products, the reuse, recycling, and remanufacturing of products, and ultimately waste management. (see Figure 4). (Hedberg & Šipka, 2021) [50].

Moreover, these technologies will help to increase awareness and expertise. among consumers and investors. Thus, consumers will get more actively involved in the transition to a circular economy. (Piscicelli, 2023) [52].

Although there are practical and theoretical cases of information flows enabling circularity, There remains a gap between the expected and largely unrealized potential to use DTs to enhance circular strategies. At present, a limited systematic comprehension is available on which areas and how digital technologies can support manufacturing companies in the implementation of circular strategies (Kristoffersen et al., 2021) [51]. Additionally, there is little support to enhance the continued and new approaches with which DTs can support the development of circular economies through smart circular strategies reaching maturity (Kristoffersen et al., 2021) [51]. Research on the assessment of environmental, economic, and The social effects of a smart circular economy are limited and dispersed (Piscicelli, 2023) [52]. It led to identifying potential factors that obstruct digital ones, which make business models' transformation.

Figure 5. Digitalization can enable a circular economy based on [50]

The supply chain lacks a unified standard for reporting and data storage as there are no frameworks for collecting and accessing data across the value chain and no agreement on common definitions, methodologies, and guidelines for data's usage (Kristoffersen et al., 2021) [51]. Also, because of missing framework conditions and a lack of knowledge and skills, many businesses do not transform their businesses and business models to gain the benefits of digitalization. In the absence of guidance, incentives, and framework conditions, the potential of digitalization to solve sustainability problems will not be realized. Even worse, in a perfect storm, digitalization may promote take-make-dispose models and overconsumption. (Hedberg & Šipka, 2021) [50].

The cost associated with digital solutions, including AI, 3D printing, robotics, and other digitally empowered new business models, can slow down their uptake (Hedberg & Šipka, 2021) [50]. Stakeholders, especially consumers, may lack the awareness, literacy, or competence to use digital solutions for purchasing more sustainable stuff or keeping and disposing of it circularly. Additionally, while digital application-based communication horizontally between various stakeholders is expected to close the solution space, it is concurrently recognised with nervousness.

Apps may effectively bring stakeholders together, uplift them, and educate them. At the same time, the current app market, with millions of applications, can be overwhelming for many people to navigate (Hedberg & Šipka, 2021) [50]. Finally, digitalization can lead to negative impacts, with the IT sector contributing 2% of global GHG emissions, like aviation. Mining, material processing, and electronics manufacturing also contribute to pollution, water stress, and biodiversity loss, with e-waste being the fastest-growing waste stream. (Hedberg & Šipka, 2021) [50].

3. Methodology

In this chapter, the research methodology for this study on the Digital Product Passport (DPP) for materials and products within the construction sector is presented. The research methodology incorporates the research design, data collection methods, data analysis approaches, and processes adopted to enhance the study’s validity and reliability. The mixed-methods research approach is utilised to cover both the breadth and depth of the subject, thereby offering a detailed analysis of the potential effects and implementations of DPPs within the construction industry.

3.1 Research Design

To answer the research questions formulated in this thesis, a multi-method approach was used to collect data. This study is a combination of qualitative and quantitative methodologies, a combination of exploratory and explanatory elements. Specifically, the qualitative research involved stakeholder meetings and a quantitative approach such as a survey. It is also important to say that the data were gathered from practical experience in the construction field.

The research design includes the following components:

Literature Review: A comprehensive review of the literature covering the Digital Product Passport (DPP), the Circular Economy (CE), and sustainability in the construction industry to identify research gaps and establish a theoretical framework. The sources reviewed include peer-reviewed journals, industry reports and articles, regulations on construction materials, and digital documentation.

Surveys: Quantitative information is collected through surveys, which are given to different groups of people in the construction industry. The survey design uses closed-ended questions, Likert scales, and multiple-choice questions that express opinions of perception, experience, and expectation about DPPs.

Interviews: Qualitative data collection is taped as semi-structured interviews with key experts and practitioners in the construction industry. The interviews seek detailed opinions and insights on the adoption of DPPs and the advantages and obstacles of DPPs.

Case Study Analysis: In this thesis, the smart roof base produced by KNAUFINSULATION is selected as a case study. It is important to consider that the objective of this case is not to develop a digital product passport for this specific product but to gain a better understanding of the concept of DPP in general. This includes identifying what type of information should be collected in a DPP, identifying stakeholders, communities, and organisations that can use DPP, and exploring the challenges associated with implementing the proposed DPP.

3.2 Data Collection Methods

3.2.1 Literature Review

The literature review was carried out using various online academic databases and websites, such as Google Scholar, Science Direct, and Research Gate. To retrieve and comprehend the relevant available information, some keywords have been used in searches of articles, conference papers, and reports related to this specific topic, such as Digital Product Passport (DPP), Circular Economy CE, Construction Product Regulation CPR, Sustainability in Construction, and Circular Economy Action Plan CEAP.

To ensure detailed coverage and high relevance, the review process included several steps. The first step was to create a list of keywords that could help address the most significant topics. It also involved conducting the search across the selected databases to obtain several sources concerned with DPPs, sustainability behaviour, and CE practices in the construction industry. The choice of keywords sufficed to reflect the maximum coverage, as the following words were included in topics: digital documentation, construction material lifecycle, recycling in construction, and environmental impact of construction. Then, based on titles and abstracts, the search results were screened for relevance. Only those sources that directly addressed the themes of digital product documentation, sustainability, and circular economy in construction were selected for a detailed review. Articles were further filtered to include only peer-reviewed journals, reputable conference papers, and authoritative industry reports. This step ensured the inclusion of high-quality and relevant literature. Duplicate entries were removed, and sources were categorised based on their focus areas, such as technological implementation, case studies, regulatory analysis, and theoretical frameworks.

An analysis of the selected literature helped identify the major patterns and themes. The existing technologies that underpin the implementation of the implementation of the DPPs were assessed and explained how these tools, such as building information modelling, help to promote sustainability in construction. The major themes uncovered included data interchangeability, material life-cycle assessment, collaboration among stakeholders, and technology integration. Subsequently, the thematic analysis highlighted the combined impact of the DPPs on promoting transparency and accountability in material use and recycling.

The review further involved an examination of current regulatory needs and standards for construction materials and digital documentation. Specifically, it focused on identifying relevant laws, both nationally and internationally, that influence the uptake and enforcement of DPPs. For instance, the Construction Product Regulation and the Ecodesign for Sustainable Products Regulations were analysed to understand the compliance levels and most accepted protocols. This considered understanding, determining, and investigating regulatory forces that triggered sustainability. The review also detailed any existing regulatory definitions, absences, or evolutions.

An essential part of the review was documenting the reported benefits and challenges related to the implementation of DPPs, which information should be included in these passports, and stakeholder engagement. This entailed outlining the extent to which DPPs enabled transparency of material traceability and the increased recycling and use of a circular economy, while determining the general obstacles, inclusive of technological, economic, and regulatory constraints, targeted at making DPPs more prevalent in the market.

Lastly, the findings have been collected to create the theoretical framework for the research. It was created to highlight the known gaps in the literature and try to build a basis for the next steps in the study. Summarising, the synthesis was meant to combine information from several studies into a cohesive vision of DPPs in the construction industry.

3.2.2 Survey

Surveys were developed to collect quantitative data on stakeholders' perceptions of Digital Product Passports (DPPs). This deductive research approach enables the gathering of standardized quantitative data from a larger sample size, facilitating easy comparison of responses (Saunders et al., 2007). Given the research objectives, employing a survey was deemed an appropriate and effective method.

The survey questions were based on the research objectives, research questions, and understanding from the literature review. Particularly, the questions included in the survey relate to the potential benefits of DPPs, the information that should be provided in DDP, the barriers faced in the adoption of DPPs as part of project management, the presumed influence of DPPs on the project outcomes, and awareness and level of maturity of the DPP-related technologies (see Appendix I). Overall, the survey employed a mix of Likert-scale, multiple-choice, and open-ended questions to obtain stakeholders' views in terms of depth and breadth, as well as to quantify perceptions. The survey was distributed via emails and online platforms to construction industry stakeholders, defined as architects, engineers, project managers, procurement officers, BIM specialists, and facility managers.

The survey's respondents were selected through the use of purposive sampling, and they had to have prior experience and knowledge of the construction sector. The sample was selected to ensure diversity among roles, types of projects, and locations based on the assumption that differences in characteristics played a role in views and opinions. The inclusion of a diverse range of professionals allowed for the development of an extensive picture of the category. The study targeted practitioners to gain the opinions of individuals most likely to be affected by DPPs.

In sum, 52 responses have been gathered for the study. In the survey, the respondents are assigned to the key stakeholder groups, as shown in Figure 6. Moreover, it is essential to mention the job titles of the respondents, which are shown in Table 2. Importantly, the survey represented companies from different countries in Europe, the Middle East, and Africa, which are presented in Figure 7.

Table 2: Respondents Job Titel Based on The Survey Result

Job Titles of The Respondents	
Architecture engineering	Industrial engineering
Aircraft Engineering	Material Engineer
BIM Engineering	Production Engineering
BIM Manager	Production Manager
Civil Engineer	Project Civil Engineer
Company Owner	Project Control Engineer
Construction Engineer	Transport planner

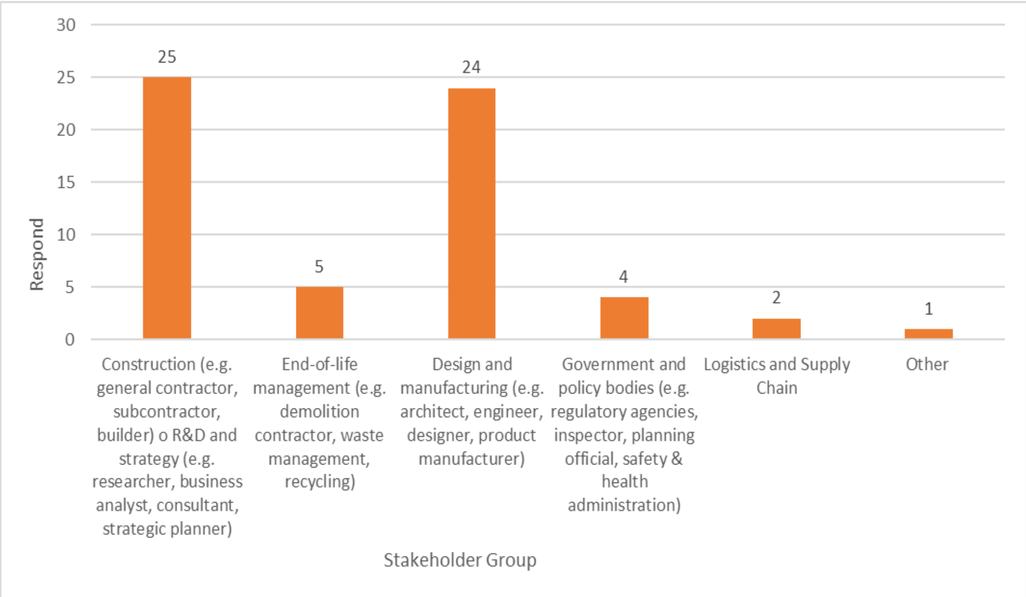

Figure 6. Distribution of stakeholder groups of the survey respondents.

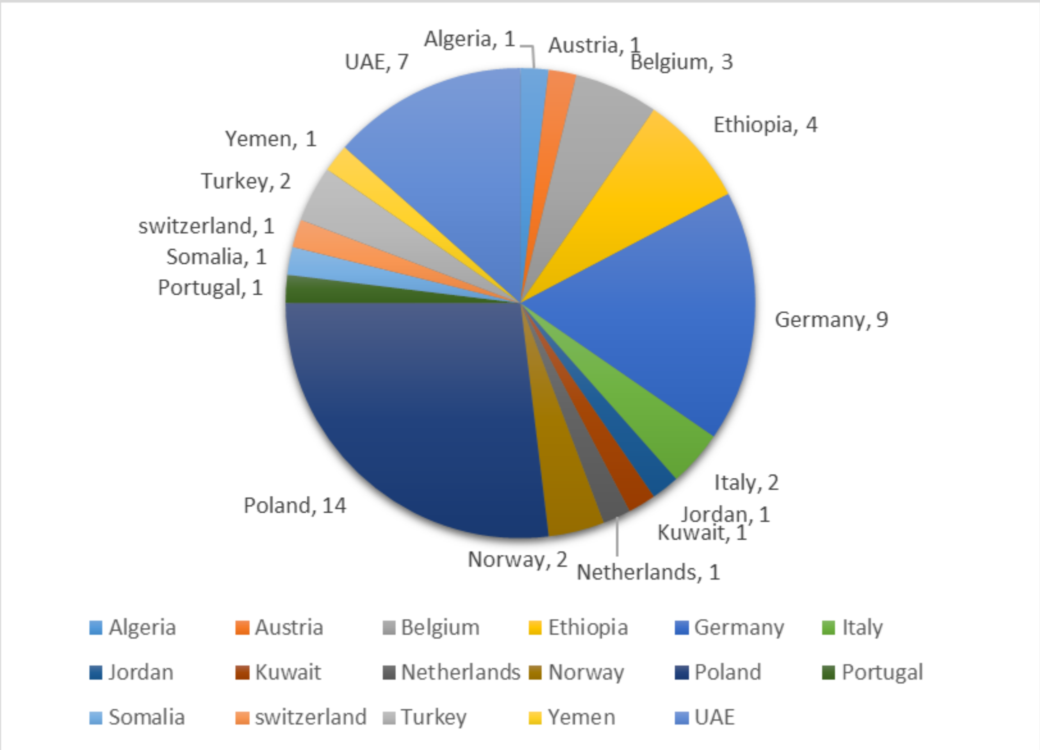

Figure 7. Distribution of survey respondents based on the country of organization.

3.2.3 Stakeholder interview

Semi-structured interviews with selected industry experts and practitioners were conducted to gather in-depth qualitative data. Since the stakeholder interview was designed to provide insight into the DPPs from the specific perspective of key stakeholders in the construction industry, Discussions were carried out to find out the benefits of DPPs, the information that was most commonly included in DPPs, and groups of stakeholders who would benefit from DPPs. Additionally, the interviews aimed to check the attitudes and current views of stakeholders about DPPs. A qualitative approach was adopted as a research inquiry as more humanistic phenomena were observed as DPPs were still in their early phases.

A semi-structured interview was chosen as a qualitative research method. In this method, the interviewer follows a structured interview guide. An interview guide was meticulously developed to ensure a comprehensive exploration of digital product passports (DPPs) in the construction industry, and it was developed using a framework developed by Kallio et al. (2016). Based on the research questions, background study, and discussions with experts in the field, an interview guide with five central themes was developed: (i) digital product passport; (ii) data and traceability for circularity purposes; (iii) benefits of a DPP; (iv) data requirements of a DPP; and (v) stakeholder benefiting from a DPP.

Overall, the interview guide contains 22 primary questions and sub-questions. Refer to Appendix II. The purpose of the guide was to facilitate open-ended discussions with different stakeholders, allowing the interviewer to ask various follow-up questions and delve into the details of the topic. This was a necessary step to gather the variety of opinions and information necessary to understand the potential and challenges of DPPs. (Silverman, 2020).

The guide began with an introduction and context provided for the interview, which explained the purpose of DPPs for the interview and outlined the DPPs concept. The subsequent questions focused on determining participants’ knowledge and perceptions of DPPs, the elements of core components, and the preexisting background. The guide also focused on the benefits of DPPs, for which recognition was given to material traceability, lifecycle management, sustainability, and how adoption of DPPs can help solve construction issues. Furthermore, challenges and barriers to DPP implementation were also articulated, including the technical, economic, and regulatory ones. Additionally, the guide included the questions that required input of information into DPPs, such as lifecycle data, material composition information, and compliance details.

Next, the guide discussed the benefits that stakeholders have from DPPs and indicated the largest groups and the cooperation between them. Finally, there were structural questions about the executives’ opinions and current perspectives on DPPs. The following trends had to be considered, arguing how well the participants were prepared for implementation: Future perspectives included DPPs as a part of the circular economy and the development of new trends and technologies.

Interview participants were selected meticulously due to the direct relation of research integrity to data quality, which has been stressed by Saunders et al. Thus, interviewees were representatives of the three primary stakeholder groups, which included the following:

Construction Industry: Participants involved in the perspective of DPP adoption for construction products and materials were the most relevant for the current study.

Design and Manufacturing: As some of the most important stakeholders, individuals from this group are particularly valuable due to their involvement in the area of DPPs.

Facility and end-of-life management: Sector representatives are related to stakeholders overseeing construction product lifecycle, which results in the most extensive information on DPPs full-scale application and advantages obtained from it.

Only three interviews were conducted, and all interviews were held via Microsoft Teams. Details of each interview can be seen in Table 3.

Table 3: Details of the interviews

Key Stakeholder Group	Interviewer Title	Interview Date	Interview Length
Design and manufacturing (Belgium)	Global Head of Market Management	18/3/2024	109 min
Construction (UAE)	Construction Manger	25/4/2024	50 min
End-of-life management (UAE)	Project Manager	2/5/2024	65 min

3.3 Data Analysis

Qualitative data was acquired in the form of transcriptions from semi-structured interviews with industry experts, as well as experience working within the construction field, and analysed using thematic analysis. Coding of the data was used to identify themes and patterns related to the benefits, challenges, and future potential of DPP methods. The thematic analysis has enabled the researchers to gain a detailed perspective on qualitative data and provide insights that were not available at first through quantitative analyses. Moreover, this technique is especially suitable to recognise, look closely at, and investigate designs around data files, then deliver highly detailed information into the qualitative (Braun & Clarke, 2006).

Thematic analysis relies on six steps. The first step was immersing myself in the data by transcribing the interviews and reading through the transcripts repeatedly. "This process led to a comprehensive understanding of the content and identified early ideas that could be subject to further analysis" (p. 6). After that, the text was systematically coded when fragments of the test emerged as meaningful and related to research questions. Each segment was assigned a code that encapsulated its meaning. Our coding work was very thorough, and this snippet is just one of many examples wherein we left no stone unturned.

The next step following coding the data was to review all codes to look for patterns or themes. Any coherent pattern large enough to be a theme in the data that was related meaningfully and significantly to answering the research questions. In this stage, similar or relevant data extracts of de-identified codes were collated into possible themes and subthemes.

The next step was reviewing the themes and subthemes to reduce them to what emerges from actual data. To do this, I carried out a two-layer synthesis process: one that involved reviewing to assess how well the themes were reflecting examples that had been coded for them, and another where I went back over the whole dataset to check if important parts of the story weren't missing from our themes.

Each theme had a clear definition and name to quickly get what the name meant in terms of representing the core gist along with it, detailing the nature and scope of themes Finally, a detailed report was produced, which outlined the themes and sub-themes identified along with supportive data extracts.

For quantitative data analysis, survey responses were conducted descriptively to summarize stakeholders' perceptions of DPPs. Quantitative style analysis, including the frequencies and percentage distributions for each question of survey; as well mean scores that's accompanied by standard deviations. Moreover, in conducting this study as well inferential statistics such as correlation analysis to examine the relationships between variables and determine statistically significant patterns.

3.4 Case of Study

This case study focuses on the Smart Roof Base, a high-class insulation base produced by KNAUFINSULATION, a market leader in the construction materials industry. This product was chosen for the analysis as an appropriate sample for the attempts to assess the potential of DPPs in the local production process because it is a relevant product for the contemporary construction sector and has the important function of improving the energy efficiency and sustainability of various building works.

The primary aim of this case study is to understand the concept of DPPs in the context of construction products and materials. In this regard, while examining the case of Smart Roof Base, it is important to discover a wide range of advantages associated with DPP application. Thus, they include better traceability of a product, increased quality control, and support for the circular economy. Also, the study should name the most important stakeholders, which are manufacturers, contractors, facility managers, and regulators.

In addition, the DPP case study will also cover the difficulties related to adaptation and implementation of these DPPs. The challenges include data collection and management, business confidentiality, ensuring the quality of data, and incorporating digital project platforms within other current digital tools like Building Information Modelling (BIM) technology.

4. Findings and Results

In this chapter, the findings of analysing the implementation of DPP for construction products and materials are presented, interpreted, and discussed. These findings are based on my experience in the construction industry as well as the meetings and surveys conducted. This chapter is divided into four sections, each addressing one specific research question of the thesis: (i) the benefits derived from the implementation of DPP; (ii) the information included in DPP; (iii) stakeholders and beneficiaries from the construction sector; and (iv) the integration of DPP with BIM technology. In each chapter of that part, findings from the construction industry, literature analysis, and qualitative and quantitative analysis are presented.

4.1 Benefits of a Digital Product Passport for Construction Product

This section is dedicated to addressing the initial research question, which is "What is the purpose of implementing the DPP for products and materials in the construction sector and its predicted benefits?". It accomplishes this by examining the potential and advantages of a DPP that have been identified in this study. Initially, issues and challenges from the construction field have been discussed, and the adoption of DPP for construction products and materials in the construction sector can solve these issues. The findings and analysis are then presented.

4.1.1 Transparency and Traceability

Based on my experience in the construction sector, I have noticed that the critical challenge that may hinder project progress as well as the achievement of the set sustainability objectives is delays in material delivery. There are a wide variety of materials that are required to be delivered in good time to be used for construction, including steel, cement, and wood. A disturbance in the supply chain could delay the supply of materials to the proponent, and a delay in the transportation of materials could delay the commencement of the project. Even worse, the materials could be limited in production, causing inflation. All these could lead to an increase in the project time, additional costs incurred, and the failure to achieve all sustainability targets.

Additionally, another challenge has been found in this study based on the analysis of the construction field that may also disrupt the project’s progress and the sustainability objectives: discrepancies with the project specifications. Most construction projects would have plans and specifications guiding the design, materials, and processes to be used on the project. However, it’s challenging to have their implementation match the initial plan that was intended. Some of the reasons that cause discrepancies include miscommunication, misinterpretation, and unknown situations on site. It may lead to more rework, increased waste, and reduced functionality, thus messing up the sustainability aspect.

The lack of sufficient information about the sustainability of construction products is an additional important issue. Most construction projects seek to maximise the number of sustainable materials and products used to ensure limited harm to the environment and waste reduction. During my work on construction projects and using several kinds of construction materials, it is often impossible to get relevant and reliable information proving the sustainability of the chosen construction product.

The scarcity of the data can be explained by the supply chain's non-transparency, the ambiguity and inconsistency of the labelling on the chosen material, and the early stages of the development of the relevant assessment criteria. Based on the results of the survey, it shows the current level of collaboration and information sharing among stakeholders in the construction supply chain is low, and only 24.3 percent of respondents see there is strong collaboration and information sharing among stakeholders. (see Figure 8).

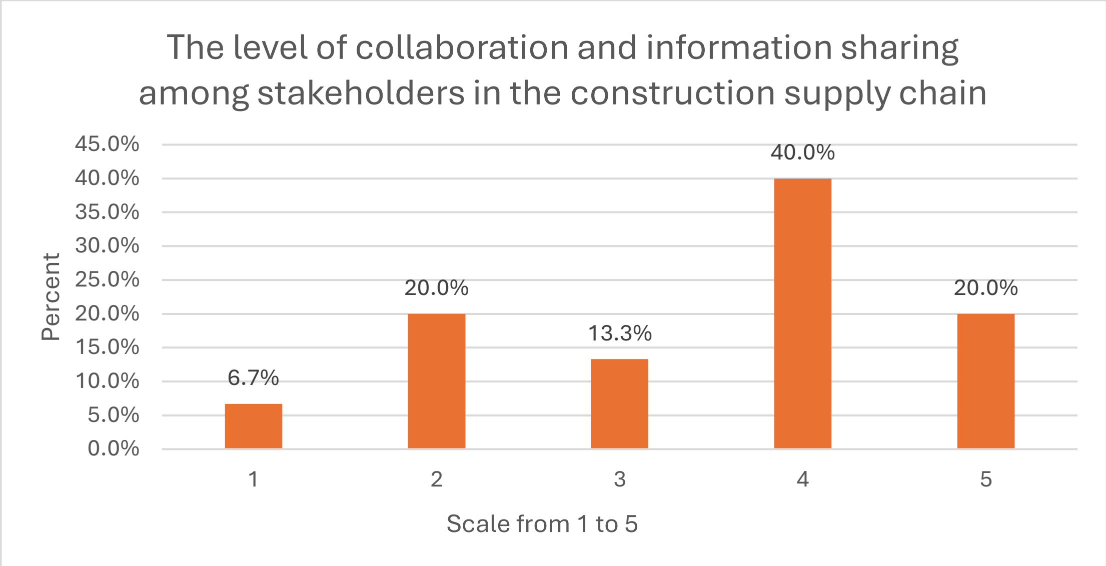

Figure 8: Survey result of the question: On a scale of 1 to 5. How would you rate the level of collaboration and information sharing among stakeholders in the construction supply chain?

To find solutions to these issues, the interviewers from the construction sector and product manufacturing explained that stakeholders in the construction industry should emphasise the importance of efficient interaction, collaboration, and transparency. In the case of DPPs, information exchange is crucial for ensuring that all relevant parties receive necessary information about building materials. By means of technology and enhanced transparency, stakeholders may mitigate delays, ensure compliance with project specifications, and make informed decisions that advance sustainability objectives. A DPP acts as a central digital store for product information consisting of detailed material composition, specifications, and environmental performance information. When all parties involved in the construction have access to such information, DPPs increase transparency and traceability in construction, thus facilitating informed decision-making and accountability.

Based on the survey results, 51.1 percent of respondents believe that DPPs will improve the transparency and traceability of product information (see Figure 9). Additionally, according to the challenges presented above for the construction sector, both the interviewers from the construction industry concur that DPPs can benefit the field with a boost in transparency and traceability in various ways.

The first advantage is that the database is centralised, which means that stakeholders in the construction supply chain can access vital information relating to products they either select, assemble, or maintain quickly and effortlessly. As such, architects will have an easier time choosing materials, while contractors ensure that they meet the necessary standards, and facility managers will prepare in adequate time for the required maintenance services. Accessible product information improves not only immediate efficiency but also transparency throughout the entire life cycle, from production through building to maintenance.

Furthermore, the DPP could enhance responsibility by creating a complete history of products and materials used in a building process. In case of any issues at any moment, the involved and affected parties were able to use the DPP to understand the cause of the problem and act accordingly. As a result, a culture of responsibility is built, trust and confidence are increased, and risks stemming from poor-quality materials and illegality are mitigated. Finally, to facilitate lifecycle management, the DPP records all related data since the product and material are manufactured to the extent of their disposal or recycling. This approach promotes the management of the entire cycle and allows the three parties concerned to track the use, maintenance, and end process of the construction materials. It also promotes the concept of the circular economy by boosting material reuse and recycling.

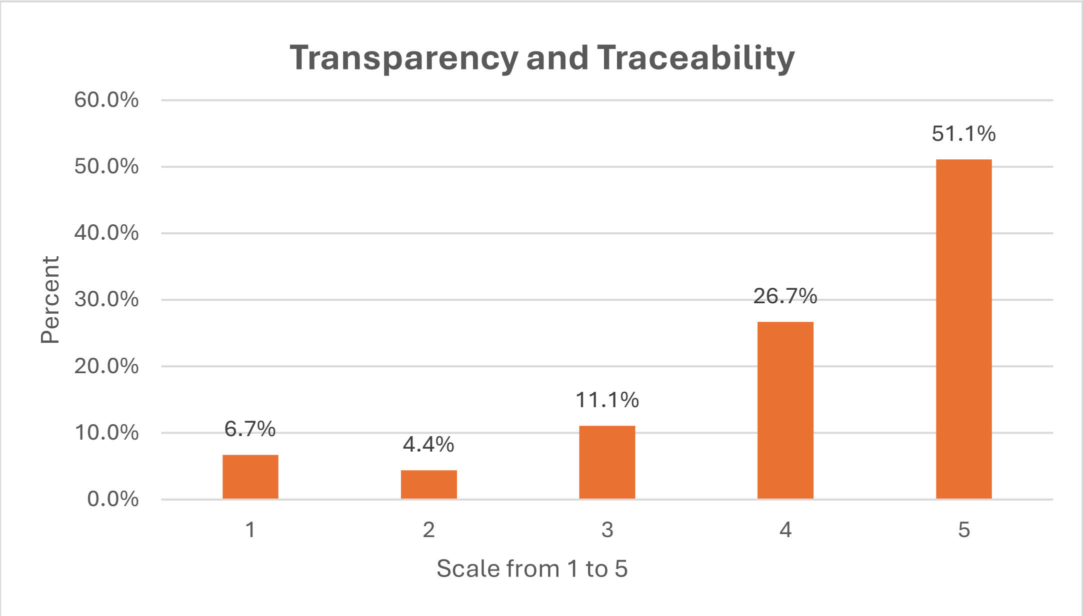

Figure 9: Survey result of the question: On a scale of 1 to 5. To what extent do you believe DPPs will improve the Transparency and Traceability of product information?

4.1.2 Sustainable Development of Construction

In this research, the problem analysis in the construction sector shows that a lack of awareness and understanding of sustainability in materials and products is one of the major problems. Many stakeholders may lead to an increase in environmental damage and social injustices caused by their construction activities due to their insufficient knowledge of sustainable principles and practices in the selection of materials. In their architectural and engineering activities on construction projects, many professionals, including architects, engineers, and contractors, are constantly bombarded with a great number of choices of materials and resources. Selecting the most sustainable materials is often challenging because the most pertinent environmental information is seldom collected, is frequently scattered throughout disparate sources, or is not available to people.

Due to the lack of accessible information about materials, such as data in the form of broad sustainability reports, it is difficult to be confident that a material is truly sustainable. As a result, decisions with huge environmental impacts can be made without even knowing about them. For example, an architect may choose a particular insulation material merely because it is cheaper than another type without knowing that this material is derived from a non-renewable source or has a high carbon footprint due to how it is produced.

Therefore, in this study, we focus on how adopting DPPs will address the lack of knowledge and information about sustainability and how we could encourage sustainable practices in construction materials and products. According to the survey results, 42.2 percent of respondents believe that DPPs will encourage sustainable practices in the construction industry (see Figure 10).

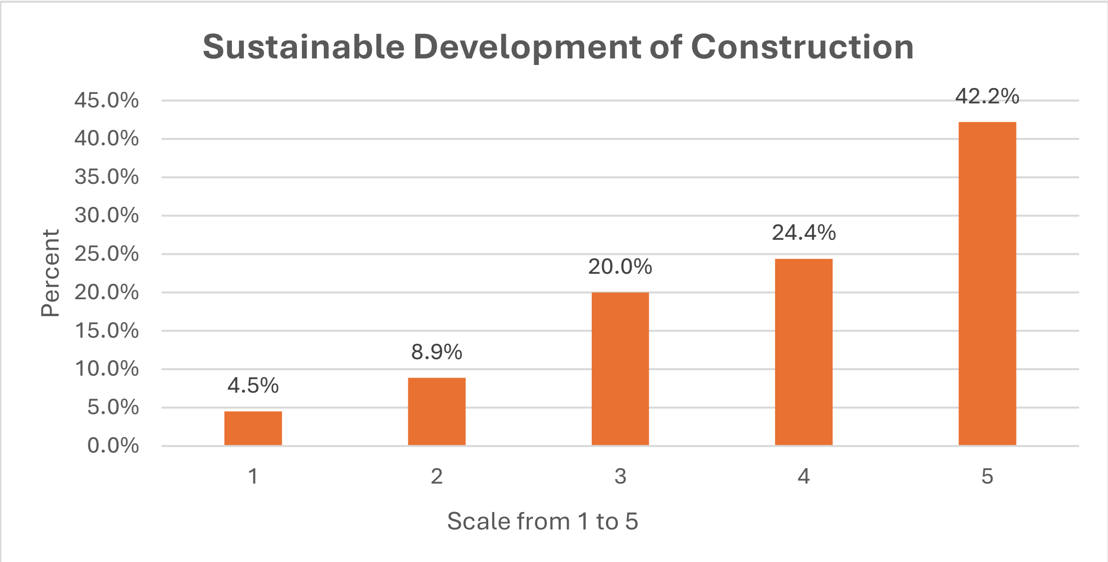

Figure 10: Survey result of the question: On a scale of 1 to 5 (Low to Hight). To what extent do you believe DPPs will encourage sustainable practices in the construction industry?

Meeting with the manufacturing product reveals that, if DPPs are created for the construction product in the near future, they have the potential to be a game-changer as a centralised platform to store and share critical sustainability information about construction materials. Just imagine that all the data that matters for the environmental impact analysis—from the manufacturing carbon footprint's calculations to the end-of-life recycling and material regeneration potential—would be stored there and have a standardised and easy metric.

One important agreement we reached in this study is that DPPs will allow architects, engineers, and contractors to decide more rationally at the design stage. In other words, DPPs offer information about the environmental impact of construction materials, their performance, and their qualities, and they help rapidly compare and determine the suitability of materials with the existing criteria. This ensures that stakeholders will be able to choose environmentally friendly materials, such as those with low carbon emissions, those made from recycled materials, or those that are recyclable, which supports the overall sustainability of the projects. Additionally, DPPs ensure that the construction supply chain remains transparent. This is because the DPPs contain the details of where the product comes from, how it is manufactured, and the environmental certifications.

To conclude, DPPs can encourage sustainable practices in the construction industry. Although designers and manufacturers may avoid using harmful products, DPPs provide a more transparent record of the environmentally harmful products used on the construction site. This forces the manufacturer to substitute the products with environmentally sustainable materials or face sanctions for the harmful materials. Ultimately, the hope is that DPPs will encourage innovation to make fewer environmentally harmful materials for the construction industry.

4.1.3 Value for Reuse, Regeneration, Recycling of Construction Product

Throughout my research in the construction industry and from my experience working in this field, I have noticed that the reuse and recycling of construction materials have numerous obstacles within the industry. The construction sector is responsible for using 40% of all extracted materials, producing one-third of total carbon dioxide emissions, and generating 40% of the total waste produced globally (Heinrich & Lang, 2019) [57].

However, the aim of this study is to anticipate how adopting Digital Product Passports (DPPs) for products and materials in the construction sector will have the potential to significantly contribute towards resolving these challenges.

Based on meetings and surveys conducted in this research, one of the major problems in reuse and recycling is the lack of visibility and information about the composition of construction materials and the nature of construction materials (see Figure 9). The lack of specific information on the built environment makes it difficult for stakeholders to identify potential reuse and recycling opportunities. Therefore, this research suggests that adopting Digital Product (DPP) Passports for construction products and materials could provide a solution for the identified problem since it would collect comprehensive data on construction products, product components, properties, and full lifecycle information. This would help suitable stakeholders find the materials that are relevant for reuse and recycling to avoid generating waste and reduce the need for new raw materials.

Another obstacle to the construction process is the division of information into separate stages. The problem is that a lot of parties are interacting in most construction projects, and they are maintaining their own datasets on materials. Such division makes it nearly impossible to accumulate details about materials and keep data in a timely manner. This can be overcome by utilising DPPs because they are a single source of truth for all relevant information about construction materials. Having a single reference on materials enhances collaboration between stakeholders by enabling information to be kept in a proper sequence. This makes it easier to track materials from their origination to disposal and allows for the identification of reuse or recycling opportunities. According to the survey results, 44.4 percent of respondents believe that DPPs will provide value for reuse, regeneration, and recycling of construction products. (see Figure 11).

Moreover, the other main reason for the European Union to develop digital product passports is to encourage the establishment of circular economy aspects in the construction sector. Consequently, this research illustrates that DPPs facilitate the advancement of design for disassembly, reuse, and recycling. By giving DPPs a role in the design and construction fields, architects, engineers, and contractors are able to have a full scope of the product materials. As a result, enabled stakeholders can efficiently make determinations concerning the choice of material, construction methods, and end-of-life avenues. As a result, this creates a more sustainable and resilient built environment. Additionally, this study suggests that DPPs will have the impact of creating online platforms (market facilitation) in the construction industry, where markets for reusable materials are formed. Therefore, contractors and other players in the sector will be able to buy and sell salvaged components, thereby promoting a more circular economy in the industry.

Beyond the environmental advantages DPPs offer, they often also represent considerable economic benefits. As this study's literature analysis shows, DPPs can help construction companies achieve significant savings by increasing the volume of materials that are reused and recycled, thus decreasing spending on new construction materials. In addition, DPPs can facilitate new kinds of business models and asset tracing, such as material leasing or sharing, thereby enhancing resource efficiency and generating new revenue.

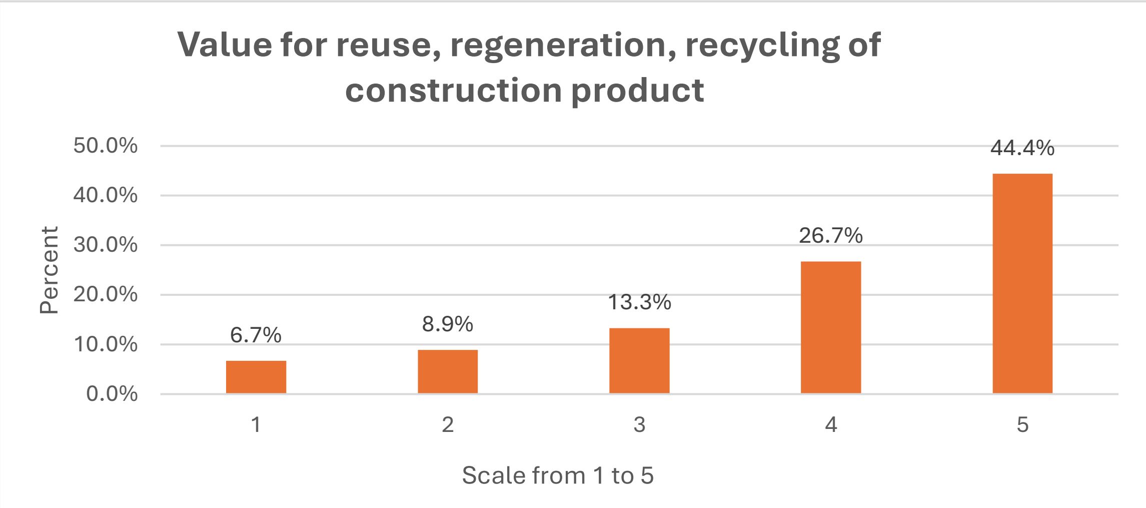

Figure 11: Survey result of the question: On a scale of 1 to 5 (Low to Hight). To what extent do you believe DPPs will give value for reuse, regeneration, recycling of construction product?

4.1.4 Closed Circuit in The Construction Sector

One more challenge that, through my vast years of experience in the field, needs to be undertaken is the shift to an environmentally sustainable one that involves a closed-loop system. However, I used qualitative and quantitative data analysis in this research to determine how DPPs can help overcome it. The results indicate that digital product passports can be a vital enabler of a closed-loop system in the construction sector. This system could allow the reuse, remanufacture, and recycling of materials and resources, thereby reducing waste. Through a closed-loop system, DPPs extend the lifespan of materials and resources, increasing resource productivity and saving costs. According to the survey results, 37.8 percent of respondents believe that DPPs will improve closed circuits or closed loops in the construction sector (see Figure 12).

The literature analysis undertaken in this study shows that DPPs would generate a digital record of all materials used in a construction project, along with the material source, its composition, and lifecycle data. The digital passports would therefore enable stakeholders to create a record of where materials are sourced and manage the materials throughout their lifecycle to the disposal point. DPP materials could also be identified for potential reuse or remanufacturing. Stakeholders should have access to information on the materials' condition and specifications contained in the passport. They would then determine whether to reuse these materials in other structures or create new products from the materials through remanufacturing. Moreover, DPPs will enhance the identification and sorting of materials to be recycled. Given that DPPs indicate deeper details on the composition of materials and their recyclability, stakeholders have a chance to ensure the recycling process is conducted in the best manner, with the right materials being sorted and recycled in line with their properties.

During a meeting with the manufacturer of the product, she explained that the Digital Product Passports (DPPs) will provide complete traceability of a product's reuse, remanufacturing, and recycling potential. This means that they can help maintain materials in the economy for as long as possible. The example given, such as a DPP, might specify that the insulating materials could be removed and reused on another building site. She also mentioned that the Digital Product Passports (DPPs) could have the potential to track materials and resources throughout their journey. This entailed information on the product's origin, manufacturing process, usage, and ultimate disassembly, allowing stakeholders to gain a full understanding of its environmental impact and ecological footprint.

Furthermore, Digital Product Passports (DPPs) will include information on the actual and potential stability, repairability, durability, and adaptability of a product to different contexts. These details also ensure that a product is designed and made with sustainability and circularity in mind. For example, a DPP file may state that a given construction material is meant to be used for a specified period without requiring substantial maintenance or is easily editable or professionally revised for reuse in other different applications.

The research also counts among the benefits of Digital Product Passports that, through data analysis of the construction sector, DPPs can enable better decision-making, which in turn results in incentivizing the implementation of closed-loop practices. DPPs serve all relevant stakeholders, offering a full view of the circular aspect of construction products, which limits waste and resource usage, as well as the environmental footprint of the construction industry. Such insights result in the creation of more sustainable built-up spaces and additional cost reductions.

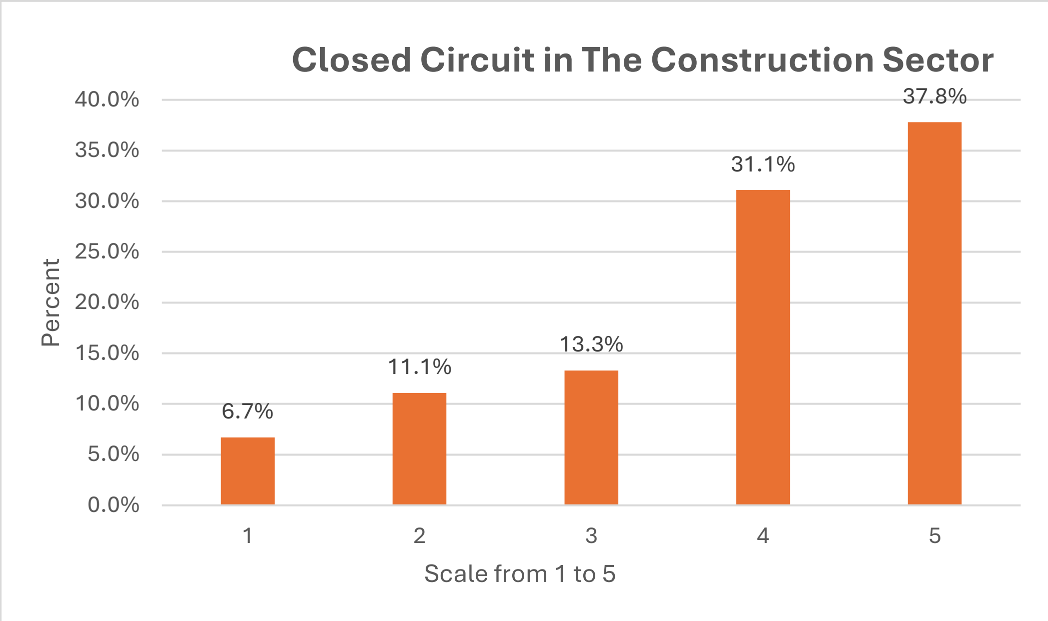

Figure 12: Survey result of the question: On a scale of 1 to 5 (Low to Hight). On a scale of 1 to 5. To what extent do you believe DPPs will Improve Closed Circuit or Closed loop in construction sector?

4.1.5 Resource efficiency (Saving Cost, Time, and Quality)

It is widely recognised that challenges such as cost, and time quality have a major impact on project outcomes and productivity within the construction industry. However, through this study and analysis of construction field issues, the potential of the Digital Product Passport has been uncovered to mitigate these issues and revolutionise the construction process.

In this study and based on qualitative and quantitative data analysis, it was found that DPPs would save resources, as recognised in one or more of the following aspects: time, costs, and quality.

Cost Reduction

In construction companies, selecting the best product in terms of total life cycle cost is a major concern for the procurement department. By enhancing the material selection, we agree that the DPPs could help the project team select the right material by comparing the whole life cycle cost. They consider the project not only based on the initial purchase cost but also other factors such as maintenance costs, BECS efficiency, and its potential to be reused or recycled. The upfront material has a shorter life expectancy in terms of cost, maintenance, and lifecycle, which makes it expensive. Therefore, through the data in the DPP project, we can achieve significant cost savings since the accounting data shows the lower-cost material. According to the survey results, 42.3 percent of respondents believe Digital Product Passports (DPPs) will help reduce costs for construction projects (see Figure 13).

Additionally, the research carried out on the problems in the realm of construction has revealed that digital product passports can contribute to cost reduction by minimising waste. We agree that by providing information on recycling and reusing construction waste, DPP could help understand the necessity of specific waste sorting and recycling activities, thereby decreasing the expenses associated with construction waste disposal. In addition, by promoting the reuse and remanufacturing of the materials, DPPs reduce the amount of new materials that have to be bought in the course of a construction project, ultimately contributing to a reduction in overall project costs.

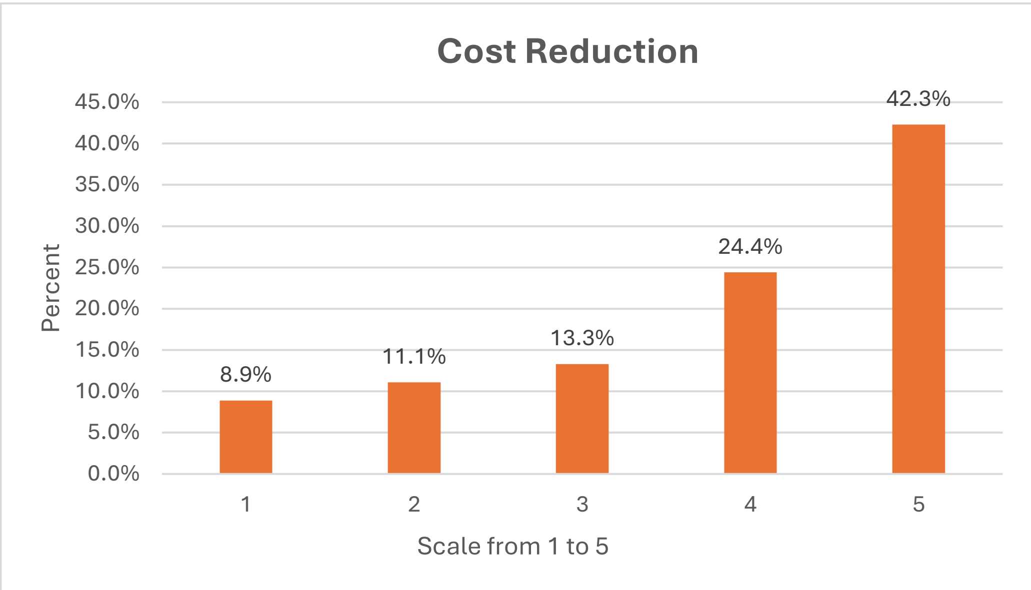

Figure 13: Survey result of the question: On a scale of 1 to 5 (Low to Hight On a scale from 1 to 5, how much do you believe Digital Product Passports (DPPs) will help in reducing costs for construction projects?

Improving Time Management

One of the key objectives for all project managers working in the construction industry is to ensure that projects are completed on time. Throughout this research, I have focused on how digital product passports could help project stakeholders manage time in projects. Based on the survey results, 46.7 percent of respondents believe digital product passports (DPPs) will help in improving time management for construction projects (see Figure 14). Additionally, it is found that DPPs could be useful for managing time in selecting appropriate materials for a project, as they simplify decision-making in the material selection procedure. Access to a vast array of information on materials stored in DPPs could result in prompt decision-making with regard to the selection of a material. Instead of wasting time searching for fragmented information, the project team could quickly review the situation, select the appropriate sustainable material, and make the right decision. Such a timely decision made as a result of the DPP would require a much shorter time for the completion of the project.

The most considerable problem we have faced in all projects throughout my work experience in the construction sector is delays in material delivery. In this study, through a meeting with a project manager in the field, we explored how Digital Product Passports (DPPs) can assist planning engineers in project time management by providing information on the delivery time of products. It was found that planning engineers could access the delivery schedules of the materials and ensure that the delivery time of the materials was synchronised with the project schedule. In such a way, the materials will be delivered on time at each stage of the project construction process. The details available could help project managers deliver products on time. Moreover, DPPs could provide planning engineers with lead-time data regarding each product from the passport. Hence, planning engineers could identify the potential delivery issues and implement changes to the construction process later. In other words, by knowing the lead times in advance, they can plan for alternative materials or adjust the project timeline as needed.

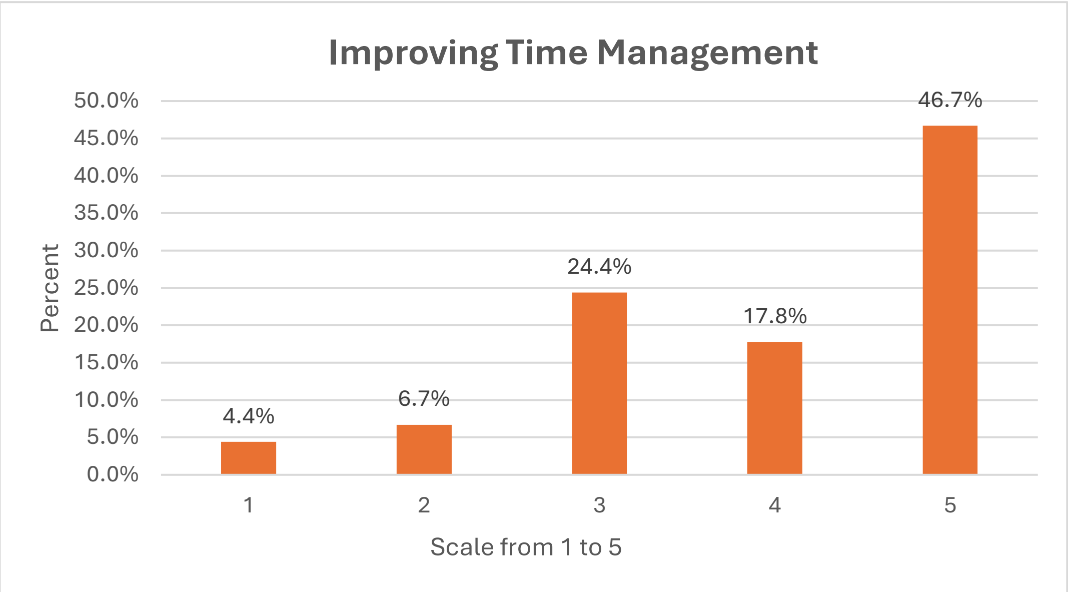

Figure 14: Survey result of the question: On a scale of 1 to 5 (Low to Hight), how much do you believe Digital Product Passports (DPPs) will help in Improving Time Management for construction Project?

In addition, Digital Product Passports (DPP) could enhance construction workflow. Meeting with product manufacturers reveals that DPP can include disassembly instructions and detailed information about a material's reusability potential. Hence, DPP enables construction teams to deconstruct buildings faster by providing the former with a comprehensive guide on how to dismantle all the parts involved. For example, if a construction team knows which of the parts of a building can be reused automatically, deconstruction becomes a dismantling exercise. The latter allows the team to salvage only the necessary parts during demolition, hence saving much time required for waste sorting and disposal. Therefore, the optimisation of the deconstruction processes ensures faster site preparation for the remaining construction stages.

Improve Quality

Finding the right material with the best quality is a major challenge among building practitioners in the industry. This is because there are so many materials available in the market, which requires considerable time and effort for project teams to compare. The assessment of the qualitative analysis from this study is that Digital Product Passports (DPPs) could make it possible for project teams to choose materials with easily verifiable claims of quality and performance. By offering consistent details about the material 's source, manufacturing methods, and performance facts and features, DPPs let project teams compare products from different manufacturers in terms of how well they will match with project requirements. This type of data-driven selection method can potentially reduce the quality-related rework that is commonly faced with the building industry.

Furthermore, when the product's manufacturers were consulted about the quality issue, the discussion revealed that Digital Product Passports may also incorporate installation guidelines and maintenance guidelines for building material in an understandable format. Therefore, by incorporating all this information and making it more available to everyone, DPPs may assist avoid installation issues and ensure that the resources are utilized in their building and maintained properly during their life. This can help eliminate the extra rework attributed to service delivery issues, resulting in a more excellent final product.

Based on the survey results, 40 percent of respondents believe Digital Product Passports (DPPs) will enhance quality improvement for construction projects (see Figure 15).

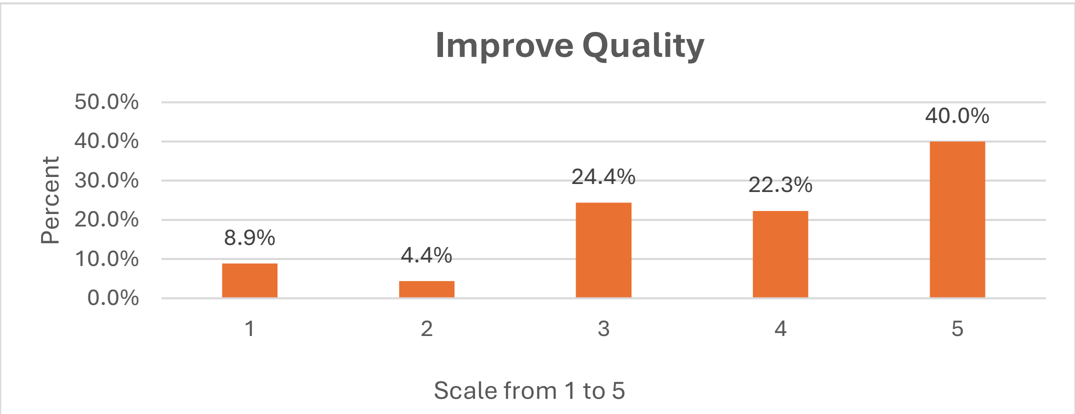

Figure 15: Survey result of the question: On a scale of 1 to 5 (Low to Hight), to what extent do you believe that Digital Product Passports (DPPs) will enhance quality improvement for construction projects?

Workload Optimization

The other advantage of implementing digital product passports identified in this study is resource efficiency. Based on the survey results, 40 percent of respondents believe Digital Product Passports (DPPs) will help reduce information overload for construction teams (see Figure 16).

In particular, the deployment of DPP could mitigate the issue of information overload. Currently, professionals have to access different sources to find the required information. When the data is consolidated on a single platform, consumers are released from the need to do so and can focus on more essential tasks, such as design, planning, and construction. Another strategy is that the project's team is well informed, and with the DPP system, every stakeholder can easily access the information that is being presented. This ensures that the communication gap is reduced, which in turn ensures that there are fewer misunderstandings. A reduction in misunderstandings will improve the decision-making process, and this will help generate a more efficient workload distribution.

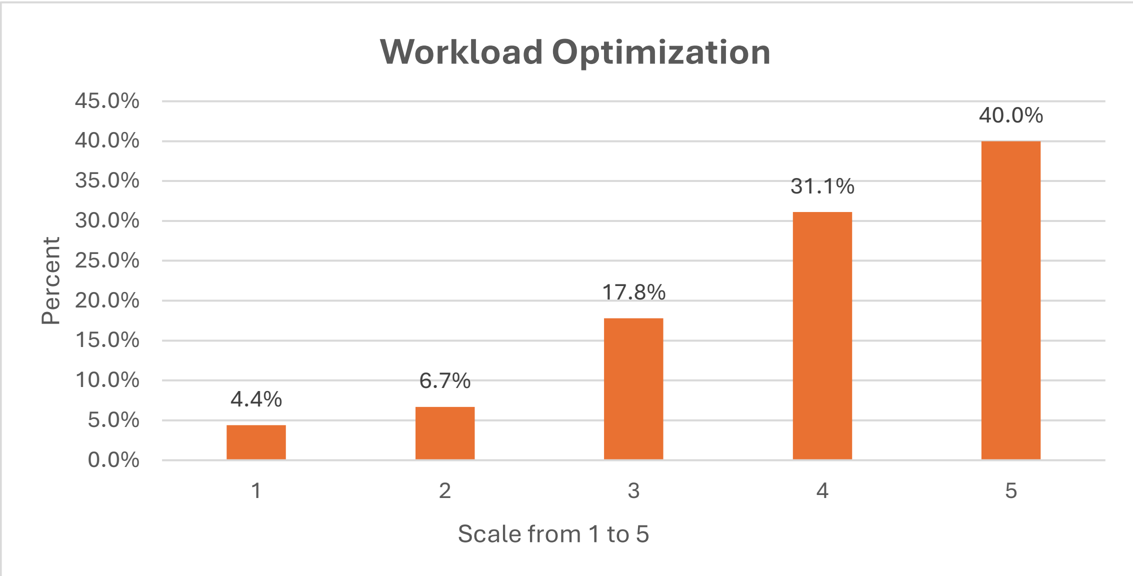

Figure 16: Survey result of the question: On a scale of 1 to 5 (Low to Hight), how much do you believe that Digital Product Passports (DPPs) will help reduce information overload for construction teams?

4.2 Information Inclusion in Digital Product Passport for Construction Product

This section aims to answer the second research question of the thesis, which is, ``What information should be included in a Digital Product Passport (DPP) for construction products and materials?" This is an examination of the information required to achieve the benefits outlined in Section 4.1.

4.2.1 Difference between technical data sheet, method of statements and Digital product passport for construction product and materials

As part of this study, the discussions with the relevant construction field stakeholders have shown that the DPP and the method of statement are often misunderstood in the technical data sheet. However, it is crucial to note that the technical data sheet and the method of statement also present critical sources of information about construction products and materials.
Nevertheless, it is important to highlight the differences between these documents and the DPP. The two documents provide the detailed specifics and properties of a product and construction activity procedures through the technical data sheet and method of statement, respectively. In contrast, the DPP can be described as an all-in-one, digital user manual for the product throughout its lifecycle. It contains specific data such as specifications, impact on the environment, regulation, and end of termination, among others. The distinctions above provide clarity on how each stakeholder can utilise the documents accordingly in a construction project.
This comparison table (see Table 4) highlights the technical data sheets, method statements, and the Digital Product Passport, emphasising their roles in the construction industry and their contributions to project execution, safety, and sustainability.

Table 4: Comparison between Technical Data Sheet, Method of Statement and DPP

Aspect	Technical Data Sheet	Method of Statements	Digital Product Passport (DPP)
Purpose	Provide detailed product information and specifications	Outline procedures and methodologies for construction activities	Serve as a digital repository for comprehensive product information throughout the lifecycle
Content	Material specifications, physical, mechanical, and chemical properties, performance specifications	Steps for executing construction activities, materials, equipment, manpower requirements, safety precautions, quality control measures	Product specifications, environmental impact assessments (embodied carbon, recyclability), regulatory compliance information, supply chain details, maintenance requirements, end-of-life considerations

Format	Document provided by manufacturers or suppliers	Written document prepared by contractors or subcontractors	Digital platform accessible through web portals or mobile applications
Use	Used by designers, engineers, contractors, and stakeholders for material selection, application, and performance assessment	Used by construction site personnel for executing work activities safely and efficiently	Utilized by stakeholders across the supply chain for decision-making, transparency, and traceability
Scope	Focuses on product specifications and performance characteristics	Focuses on construction methodologies, safety, and quality control	Covers the entire lifecycle of construction products and materials
Presentation	Typically presented as a document or datasheet	Written in narrative format with step-by-step instructions	Presented as a digital interface with standardized data fields
Regulatory Compliance	Provides data for compliance assessment but does not detail methods of compliance	May include references to relevant regulations and standards	May include regulatory compliance information along with product data
Interactivity	Static document, limited interactivity	May require updates or revisions based on project-specific requirements	Dynamic platform with potential for real-time updates and collaboration
Integration with BIM	Often integrated into BIM models as product libraries	May be referenced in BIM models for planning and coordination	Can be linked to BIM models for seamless access to product information

4.2.2 Detailed information included in Digital Product Passport for Construction Product and Material

As stated in the study's introduction and based on literature analysis, it was noted that the primary purpose of DPP is the conversion of the construction sector from a linear economy into a circular one. As a result, the details on the sustainability, reuse, recycling, and regenerative construction materials application must be included in the digital product passport. Additionally, it should provide information to enhance the implementation of a closed-circuit system within the construction industry, which leads to cost and time savings during the construction process.

Additionally, to leverage the advantages of the Digital Product Passport (DPP), as outlined in Section 4.1 of this thesis, this study identified the crucial information that should be incorporated into the DPP for construction products and materials. Through a thorough analysis of the construction field and its specific requirements, qualitative analysis, and data from the study survey, this information has been categorised into several key categories, each with its own set of sub-information. Based on the survey results, most of the respondents showed that a digital product passport should include several types of information, such as technical specifications, environmental impact, end-of-life options, manufacturing process, and material composition (see Figure 17).

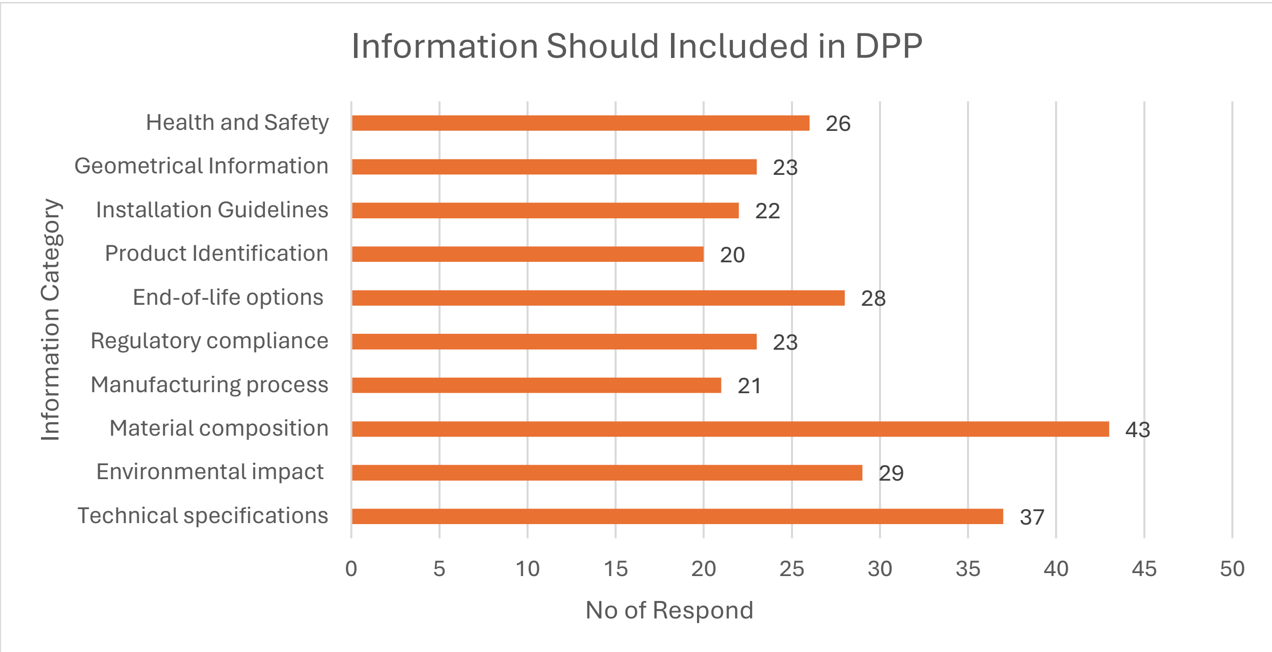

Figure 17: Survey result of the question: Which types of information do you think should be included in DPPs for construction products?

Moreover, this study identified the essential information that needs to be included in the DPP of construction products and materials, which has been determined based on an in-depth examination of the construction industry. The information is categorised into several main categories with a variety of sub-information, as shown in Table 5.

Table 5 summarises the key information that should be included in a Digital Product Passport (DPP) for construction products and materials, focusing on sustainability, performance, and closed-loop systems.

Category	Information
Product Identification	Product Name: Clear and identifiable name of the product (brand name and generic name)
	Product Category: Classification of the product type (e.g., Brick, Insulation, Concrete Mix)
	Unique Product Identifier (optional): Unique identifier for easy tracking (e.g., QR code, serial number)
	Manufacturer Information: Contact details of the manufacturer for inquiries.
Material Composition and Ingredients	List of Ingredients: Detailed breakdown of materials used in the product, including percentages (consider including recycled content separately).
	Chemical composition and hazardous substances, if applicable.
	Information on recycled content or renewable materials.
	Traceability of Raw Materials: Information on the origin and sourcing of raw materials, promoting responsible procurement practices.

Performance Characteristics	Technical Specifications: including dimensions, weight, and key performance metrics relevant to the product's functionality (e.g., strength, durability, fire rating, thermal insulation). Technical data sheets providing detailed information on the properties and characteristics of construction products and materials.
	Performance testing results.
	Warranty information and Expected Lifespan: Estimated duration of the product's functionality under normal use conditions.
	Compliance with Standard and Performance Testing Results: Reference to relevant industry standards and certifications the product meets (e.g., fire resistance, durability)
Quality Standards	Quality control measures and standards
	Conformance to quality management systems (e.g., ISO 9001)
Compliance and Certification	Compliance with relevant regulations and standards (e.g., CE marking, ASTM standards)
	Certifications for environmental performance eg (e.g., LEED, BREEAM)., quality management, and safety standards eg. (OSHA).
Installation Guidelines	Detailed installation instructions and procedures
	Sequential steps for proper installation
	List of tools and equipment required for installation
	Recommended safety gear and personal protective equipment
	Safety precautions and guidelines for installation
Maintenance and Care	Procedures for routine maintenance and care
	Recommended maintenance schedule and activities
	Instructions for cleaning, repair, and maintenance tasks
	Guidelines for addressing common issues and repairs
	Maintenance requirements and guidance for prolonging product lifespan

Sustainability Focus for Closed-Loop Systems	Embodied Carbon: Data on the CO2 emissions associated with production and transportation, promoting low-carbon materials
	Life Cycle Assessment (LCA) Summary (optional): Key environmental impact data throughout the product lifecycle, including embodied carbon, resource consumption, and end-of-life options
	Design for Disassembly: Information on whether the product is designed for easy dismantling to facilitate reuse of components at the end of its lifespan
	Remanufacturing Potential: Indicate if the product can be remanufactured back into its original form or a new product at the end of its lifespan.
	Recyclability: Details on the product's recyclability, including the type of recycling process it's suitable for and any special considerations
	Regenerated Content: Specify if the product incorporates bio-based or regenerated materials suitable for composting or returning to the natural cycle at the end of life.
	Compliance with waste management regulations
Environmental and Social Impact	Life cycle assessment (LCA) data, including carbon footprint, energy consumption, and water usage
	Environmental certifications and labels (e.g., Environmental Product Declarations - EPDs)
	End-of-life considerations, such as recyclability and disposal methods
	Details of labor practices and social responsibility initiatives
	Compliance with labor standards and ethical sourcing policies
Health and Safety	Safety Data Sheet (SDS): Link to a comprehensive document outlining potential hazards and handling procedures.
	Volatile Organic Compound (VOC) Emissions: Level of VOCs emitted, if applicable, for improved indoor air quality
	Hazard identification and risk mitigation measures.

Supply Chain and Supplier Information	Traceability of raw materials and supply chain transparency
	Information on suppliers, subcontractors, and manufacturing locations
	Approved list of suppliers for the product or material.
	Details of authorized distributors and manufacturers
	Criteria for supplier qualification and selection
	Quality assurance requirements for suppliers
	Process for evaluating supplier performance
	Performance metrics and criteria for evaluation
	Required time to supply the ordered materials to the specific location
Digital Connectivity	Integration with Building Information Modelling (BIM) platforms for digital modelling and simulation
	Compatibility with construction management software for project planning and tracking
Additional Information for Closed-Loop	Disassembly Instructions: Clear instructions for dismantling the product, promoting efficient deconstruction
	Take-Back Programs: Information on any manufacturer take-back programs for reclaiming the product for recycling or remanufacturing
	Marketplace for Reuse: Links to platforms where salvaged components can be matched with potential buyers, facilitating reuse within the industry
User Feedback and Reviews	Customer reviews and feedback on product performance and satisfaction
	Case studies or project references showcasing successful applications of the product

4.3 Stakeholders Benefiting from the DPP in the Construction Sector

This section aims to answer the third research question of the thesis: "Which stakeholders within the construction sector will derive advantages from the DPP?" While numerous stakeholders can benefit from the DPP, this section will focus specifically on how stakeholders within the construction industry can achieve the benefits outlined in Section 4.1, as this study relies on collecting and analysing data from this sector (see Table 6). Therefore, this section explores the key stakeholders in the construction industry who stand to benefit from the adoption of DPPs and how these advantages manifest in their respective roles.

According to the survey results, the majority of the respondents show that there are several stakeholders in the construction industry who can benefit from adopting the digital product passport. (see Figure 18).

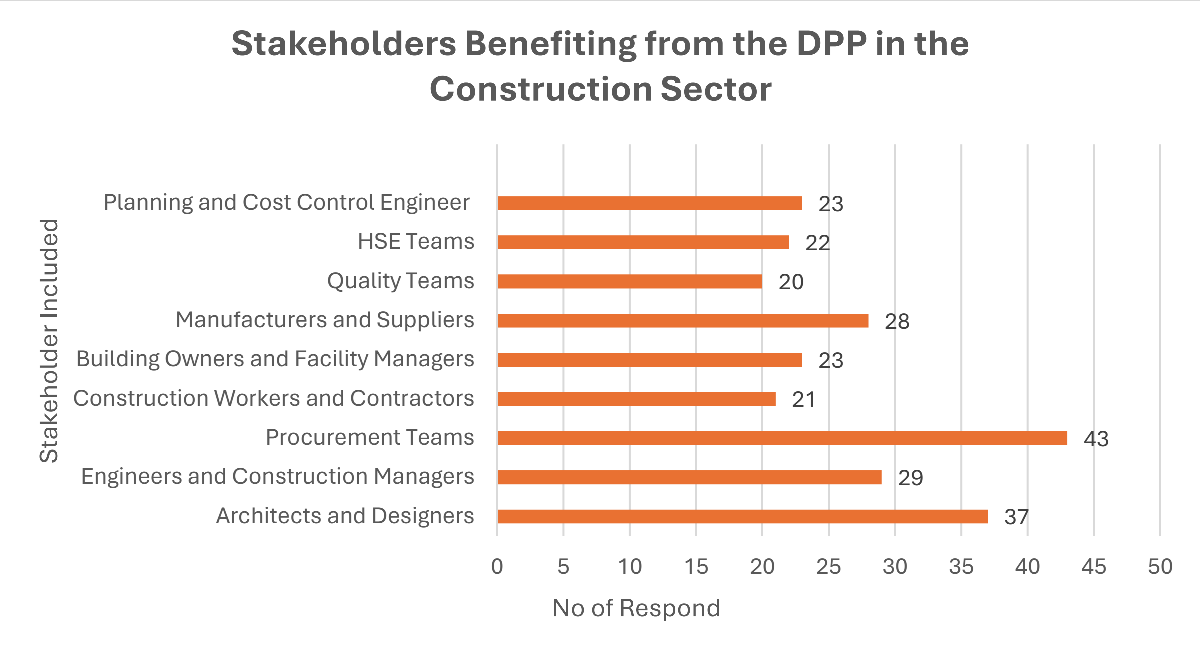

Figure 18: Survey result of the question: Which stakeholder in the construction sector do you think could get benefits from adopting DPPs for construction products?

A meeting with a project manager manages a construction project in the UAE shows that one of the significant DPP beneficiaries are architects and designers. This stakeholder suggests that for architects and designers, DPPs may be essential, acting as a single warehouse for full data on construction materials. This way, they can make choices based on data while meeting the aesthetic and functionality demands of a project. Moreover, time and effort spent on material selection have massively decreased, and all the picks meet quality and environmental regulations and compliance and support the sustainability targets of the project.

Furthermore, he also reiterated that engineers and construction managers also benefit from the DPPs. The reason is that the technical specifications and performance properties of these materials, which are critical to achieving structural stability and safety, are readily available through the DPPs. This is followed by enhanced accuracy in project formulation and feasibility in project implementation.

Additionally, we strongly believe that procurement teams are among the primary beneficiaries of Digital Product Passports (DPPs). DPPs simplify the complexity surrounding the supply chain for procurement executives, eliminating information overload and diminishing the time spent gathering data. They simplify multiple information batches into a single platform, thereby allowing them to focus on negotiating favourable terms and the schedules in which their input material arrives. The DPP provides insightful information on the source of the supply chain and its environmental pillars for proper sustainable supply chain decisions.

Other stakeholders include construction workers and contractors who are directly involved in projects' implementation on site, and they also greatly benefit from DPPs. Construction workers and contractors stand to gain from detailed disassembly plans in (DPPs) for efficient building deconstruction and reusability. Moreover, DPPs not only allow contractors to make more efficient use of the resources available, but they also work as a key process improvement for managing construction from a stage-by-stage and overall perspective.

Based on the literature analysis in this study, building owners and facility managers can have significant advantages from digital product passports. DPPs aim to help building owners' sustainability targets by providing information about materials' embodied carbon and environmental footprint. They can easily make decisions regarding the optimisation of lifecycle costs and energy efficiency. Furthermore, the facility manager can access the passport with maintenance advice to ensure that building components have long life spans by taking care of them properly as well as planning for future renovations and deconstruction.

Finally, Digital Product Passports DPPs also benefit manufacturers and suppliers. As a marketing tool developed by a manufacturer, DPPs may help manufacturers raise market share of attention for sustainability and performance differences and provide transparency that can help differentiate products. Quality teams are assisted by DPPs to reduce their material handling expenses, comply with regulations, reduce rework, and enhance quality control.

Table 6. Perceived Stakeholders Benefiting from the DPP in the Construction Sector based on participants responses.

Stakeholder	Expected Benefits of DPPs
Architects and Designers	Centralized data access, data-driven decision-making, reduced material selection time, compliance with regulations.
Engineers and Construction Managers	Ready access to technical specifications, improved project accuracy, enhanced structural stability.
Procurement Teams	Simplified supply chain complexity, reduced information overload, consolidated data, better negotiation, and scheduling.
Construction Workers and Contractors	Detailed disassembly plans, improved resource management, enhanced construction process efficiency.
Building Owners and Facility Managers	Information on materials' environmental impact, lifecycle cost optimization, maintenance advice, planning for future renovations.
Manufacturers and Suppliers	Marketing tool for sustainability, increased market share, transparency, and product differentiation.
Quality Teams	Reduced material handling expenses, compliance with regulations, reduced rework, enhanced quality control.

4.4 Integration of Digital Product Passport with BIM Technology

This section aims to answer the fourth research question in the thesis: What are the advantages of combining DPP (Digital Product Passport) with BIM (Building Information Modelling)? The Digital Product Passport (DPP) serves as a comprehensive repository of accurate and up-to-date information on construction products and materials, as discussed in Section 4.1.1 of this study. I will analyse the expected benefits of integrating DPP and BIM technology, considering the insights gained from analysing data in the construction field and gaining an understanding of how BIM technology works.

Based on this study, considering the insights gained from analysing data in the construction field and gaining an understanding of how BIM technology works., there are several expected benefits from the integration of DPP (Digital Product Passport) with each dimension in Building Information Modelling technology, such as 3D, 4D, 5D, 6D, and 7D, to the construction industry (see Table 7). The following points show how each dimension in BIM can integrate with DPP:

In 3D BIM (geometric modelling), DPP data can be shown within 3D BIM models, so stakeholders can see the physical characteristics and attributes of the construction products. Moreover, by combining DPP data with the 3D BIM model, clashes between different components can be identified early in the design process, allowing selected products to fit in with the building geometry.

In 4D BIM, which is dedicated to time management, planning engineers can use digital product passport data such as material availability, delivery times, and installation sequences to optimise construction schedules by linking construction schedules to DPP data, which provides trustworthy and updated information about construction products and materials.

In 5D BIM, which is dedicated to cost management, cost estimators and cost control engineers can use digital product passport information, considering many factors such as material prices, transportation costs, and lifecycle expenses. Additionally, throughout the construction process, stakeholders can track material costs and modify budgets in accordance with the latest updates to DPP information available in 5D BIM models.

In 6D BIM, which is concerned with sustainability management, using DDPs, sustainability goals will be achieved. These passports provide extensive information on the environmental impacts of a given material, including embodied carbon, energy consumption, and recycling likelihood. Such knowledge helps stakeholders evaluate material offers based on their environmental footprint, allowing them to earn LEED or BREEAM accreditation. The DDPs also enable the gathering of information required for complete lifecycle assessments (LCA), which is vital to projects to understand the lifespan environmental effects of the material and systems utilised in the structure.

7D BIM, which is dedicated to Facility Management, DPP information can help the Facility Manager and his team get useful sources of asset information that may be used in 7D BIM models. It gives important data on the performance, composition, and maintenance needs of building materials and provides information about materials and equipment suppliers and their warranties.

Table 7. Integration of Digital Product Passport with BIM Technology based on Data Analysis.

BIM Dimension	Benefits from DPP Integration
3D BIM (Geometric Modelling) building geometry.	DPP data within 3D BIM models reveals physical characteristics and attributes of construction products. It helps identify clashes early in the design process, ensuring product compatibility with building geometry.
4D BIM (Time Management)	Planning engineers use DPP data like material availability and delivery times to optimize construction schedules, linking them to reliable and updated information.
5D BIM (Cost Management)	Cost estimators use DPP information on material prices, transportation costs, and lifecycle expenses to track and adjust budgets according to the latest data.
6D BIM (Sustainability Management)	DPP integration provides data on the environmental impact of materials, such as embodied carbon and lifecycle assessments, helping stakeholders make sustainable choices and achieve project sustainability goals.
7D BIM (Facility Management)	Facility managers access DPP information for asset management, including performance, composition, maintenance needs, supplier details, and warranties.

5. Results of the Case Study Analysis

This chapter aims to improve the understanding of Digital Product Passports (DPPs) by presenting and discussing what main information is needed for a DPP on the Smart Roof Insulation material manufactured by KNAUFINSULATION. This chapter also serves the purpose of establishing who the main stakeholders in the construction sector that could benefit from the information provided by DPPs are. Finally, this chapter briefly discusses the challenge and issue of DPP implementation.

The main applications for the Rock Mineral Wool (RMW) concerned products are thermal and sound insulation of roofs.

5.1 Geometrical information

This study initially focuses on determining the essential geometrical data that should be included in digital product passports for the selected insulation material. It then looks at the advantages of being aware of this type of information and how it can be beneficial to the stakeholders involved in the construction industry. Moreover, it is accompanied by the 3D model of the product that has been designed with Revit 2023 (see Figure 19). It depicts the advantages to different parties in the construction sector that could be derived from knowledge of the selected information, for instance, when DPPs integrate with BIM technology.

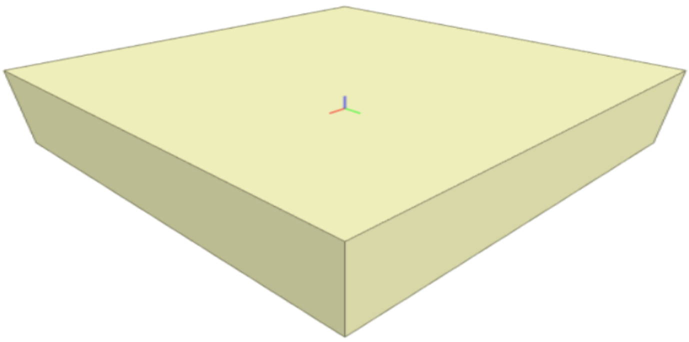

Figure 19: 3D modelling for Smart Roof Thermal Insulation which was designed with Revit 2023.

Smart Roof Thermal Insulation's geometrical data involves multiple dimension-related specifics important for its implementation and thermal performance. This includes dimensions, specifying the lengths, widths, and heights of the insulation panels or rolls. Furthermore, they include the thickness of the layer, which is how much resistance against heat the material can provide. Another important geometric feature is the density of the material, which measures how much of it is inside the defined volume and, hence, how well it can prevent heat flow (see Figure 20). Finally, the shape of the insulation also affects how it can be laid and what roof structures it is optimal for. In other words, all these geometric properties together determine how well the insulation material performs in place over time (performance), how long it will endure out under fire (durability), and which roofing systems it rides on without problems.


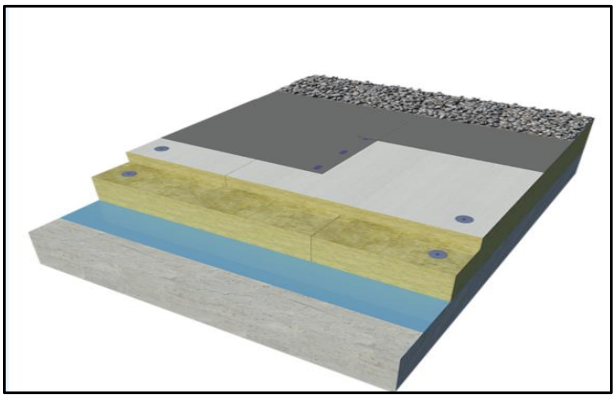

Figure 20: Smart Roof Thermal Insulation (140 mm) Thickness = 40-200 mm, Length= 100-120 cm, Width = 40-60 cm.

They are available as lamellas, slabs, or boards, and possibly rolls. The density range for rock mineral wool goes from 25 to 200 kg/m³.

5.1.1 Construction Stakeholders Benefit from The Inclusion of Geometrical Information.

As mentioned previously, this part of the research examines which stakeholders could benefit from knowing the geometric information on smart roof insulation material. Several stakeholders can benefit from this information that was revealed during our meeting with manufacturers of these products. Furthermore, each stakeholder can use this information differently based on their role in the construction industry. For instance, architects and designers use geometrical information to integrate the insulation material into building designs, define the total thickness of the roof floor, and avoid clashing with other elements and services. A smart roof base is a board designed as the bottom layer of a flat roof composition. Additionally, the structural engineer must know the density and the unit weight of the material during the structural calculations.

Another stakeholder requiring this information is the material supplier and transportation companies. They use geometrical data to determine the most suitable method of transportation and the appropriate truck size to deliver the required amount to the destination. Additionally, another stakeholder who needs this information during the construction phase is the project's storekeeper, who relies on this information to find suitable storage locations for the materials. Furthermore, labourers responsible for installing the materials and shifting them within the construction site also require access to geometrical data.

Building owners and developers could also benefit from knowing the geometric information. Knowing the geometric properties of the insulation material enables building owners and developers to comprehend its thermal performance. They can also analyse the R-value and U-value of the insulation since the values help determine its ability to resist heat flow. Therefore, this knowledge provides access to an effective collection of thermal insulation materials that results significantly in ensuring the building optimises insulation to reduce heating and energy costs.

5.2 Technical information

In compliance with the Construction Product Regulation (CPR), the Digital Product Passport (DPP) should include not only the characteristics related to the environment but also technical product characteristics. The purpose of DPPs is to enable the exchange of information and ensure compliance with regulatory requirements in the context of the construction industry. In this regard, the study covers technical information to be included in DPPs for smart roof materials based on data analysis of technical data sheets provided by product manufacturers.

The products and their technical characteristics meet a number of technical requirements. Technical data is divided into two main categories: technical parameters and technical specifications, which cover all product technical information.

5.2.1 Technical Parameters

The technical parameters for smart roof insulation material encompass several values (see Table 8):

Thermal conductivity (λ): λ is the measure of the rate at which heat can flow through the material for a given thickness and temperature difference. It is measured in watts per metre per Kelvin subscript (W/mK), where it defines how well the material can insulate.

R-value: This is a measure of how much an insulating material can resist heat flow. The R-value is defined as the ratio of the material's thickness to its thermal conductivity, and it is expressed in square metres of kelvin per watt (m2K/W). A higher R-value, therefore, means there is better insulation.

Density: This characteristic is related to the mass of an insulating material per unit volume; usually, it is measured in kilogrammes per cube metre (kg/m3). Density affects the specific thermal capacity, rigidity, and noise reduction of insulation methods.

Thickness. This is the dimension of the insulation material, representing the perpendicular to its surface. The thickness is measured in millimetres or inches. It directly determines the overall thermal resistance and insulation efficiency.

Table 8: The technical parameters for Smart Roof Insulation for different thickness

Technical Parameters						
Thickness	Thermal conductivity λ	Thermal resistance R	Length	Width	Pcs	Qty
(mm)	(W/mK)	(M2k/W)	(mm)	(mm)	palette	palette(m2)
20	0.035	0.55	1200	1000	120	144
30	0.035	0.85	1200	1000	80	96
80	0.035	2.25	2000	1200	16	38.4
100	0.035	2.85	2000	1200	13	31.2
120	0.035	3.4	2000	1200	11	26.4
140	0.035	4	2000	1200	9	21.6
150	0.035	4.25	2000	1200	8	19.2
160	0.035	4.55	2000	1200	8	19.2
180	0.035	5.1	2000	1200	7	16.8
200	0.035	5.7	2000	1200	6	14.4
220	0.035	6.25	2000	1200	6	14.4
240	0.035	6.85	2000	1200	5	12

These technical specifications are crucial for evaluating the performance, suitability, and compliance of Smart Roof Insulation material for specific construction applications.

5.2.2 TECHNICAL SPECIFICATIONS:

The technical specifications for smart roof insulation material include (see Table 9):

Thermal conductivity: Indicates the rate at which heat passes through the material.

Reaction to Fire: Describes the material's behaviour when exposed to fire, including its flammability and smoke production.

Melting Point: The temperature at which the material changes from a solid to a liquid state.

Water Vapour Diffusion: Measures the material's ability to allow water vapour to pass through it.

Specific Heat Capacity: The amount of heat required to raise the temperature of the material by one degree Celsius.

Tensile Resistance: Indicates the material's ability to withstand pulling forces without breaking.

Compressive Strength: Measures the material's ability to withstand compressive forces without deforming.

Point Load: Describes the maximum load that the material can support at a specific point without failing.

Water Absorption (Short-term): The amount of water absorbed by the material in a short period, usually 24 hours.

Water Absorption (Long-term): The amount of water absorbed by the material over an extended period, such as several weeks or months.

Thickness Tolerance: describes the acceptable deviation from the specified thickness of the material.

Designation Code: A code used to identify and classify the material according to specific standards or regulations.

Table 9: The technical specification for Smart Roof Insulation material

TECHNICAL SPECIFICATIONS				
Property	Symbol	Value	Unit	Stander
Thermal conductivity	Λ	0,035	W/mK	EN 12667
Reaction to fire	_	A1	_	EN 13501-1
Melting point	_	>1000	°C	DIN 4102/ T17
Water vapor diffusion	µ 1	1	_	- EN 12086
Specific heat capacity	Cp	1030	J/kgK	EN ISO 10456
Tensile resistance	TR	7,5	kPa	EN 1607
Compressive strength	CS(10)	30	KPa	EN 826
Point load	PL(5)	300	N	EN 12430
Water absorption (short-term)	WS	≤ 1	kg/m2	EN 1609
Water absorption (long-term)	WL(P)	≤3	kg/m2	EN 12087
Thickness tolerance	_	15	_	EN 13162
Designation code	_	MW-EN 13162-15-WS-WL(P)-MUI	_	EN 13162

These technical specifications are essential for evaluating the performance, safety, and suitability of Smart Roof Insulation material for various construction applications.

5.2.3 Construction Stakeholders Benefit from The Inclusion of Technical Information

Through the analysis, various stakeholders responsible for the construction industry benefit from adding technical information about smart roof insulation material to the Digital Product Passport (DPP). This technical information is important for architects to make sure that the insulation material meets design specifications and to develop energy-efficient, sustainable building designs. Furthermore, detailed technical data enables engineers to continue identifying the structural integrity and thermal ability of the insulation material that are essential in incorporating the building system at all.

In addition, facility managers and project managers are two of the main stakeholders who obtain the most benefit from technical information. Facility managers should have the technical data on the insulation material to know about the maintenance needs for it and other things that can help the building's long-term performance. In contrast, the project managers will employ it to plan and coordinate their insulation materials' usage in their building projects.

Technical specifications also assist procurement officers, who can use this information to make decisions about purchases and ensure that materials acquired will meet the required standards and perform as specified. Moreover, the technical information helps regulatory authorities confirm compliance with building codes and energy efficiency standards, as well as requirements regarding environmental protection, to guarantee that materials promote safe and sustainable construction.

5.3 Environmental and Sustainable Information

According to this study, the main function of digital product passports is to facilitate the transition from a linear economy to a circular economy. As for the smart roof insulation material, the DPP should contain detailed and comprehensive information regarding the environmental impact of the product.

Furthermore, the DPP should present and provide data on the material's recyclability or reusability, which should support the notion of it being sustainable. Overall, the DPP should cover and contain the sustainable features of the product, making sure that all the stakeholders are provided with data on the product's environmental and sustainable performance.

Moreover, DPP contains information on the embodied carbon of materials, which represents the total carbon dioxide emissions of a material produced, transported, and installed as part of the product. It also includes information about their end-of-life phase, which details whether they can be recycled or disposed of in a landfill, which can help with efficient planning of the demolition and ensure sustainable waste disposal. Furthermore, DPPs contain information on the energy consumed in the production of materials. However, all environmental and sustainable information for smart roof insulation can be found in the Environmental Product Declaration, which is attached in Table 10.

5.3.1 Construction Stakeholders Benefit from The Inclusion of Environmental and Sustainable Information

This study reveals that multiple stakeholders in the construction industry gain advantages from incorporating environmental and sustainable information about smart roof insulation material into the Digital Product Passport. Environmental and sustainability information provided in DPPs enables architects and designers to make informed decisions regarding material selection. It enables them to use ecological materials in their designs, which help built environments ensure overall sustainability. In addition, DPPs offer an overall benefit for builders and contractors by providing detailed information on the environmental impact of insulation materials as well as their sustainability characteristics. Allowing the project teams to select their own materials based on common parameters facilitates meeting project sustainability goals and regulatory requirements, which in turn improves projects and reputations.

Moreover, the environmental and sustainability information available in DPPs could also help property owners and developers develop sustainable buildings. If owners choose insulation materials with lower embodied carbon and higher recyclability wherever they can (and even better, everywhere), they will have an overall lighter environmental footprint while providing a unique selling proposition for environmentally conscious tenants or buyers. Consumers benefit from DPPs with enhanced visibility of the environmental and sustainable profile of insulation materials used in construction work. This enables home seekers and renters to make more environmentally sustainable decisions when selecting or purchasing properties as per their values and preferences.

5.3.2 Advantages of Smart Roof Insulation over Foam insulation:

While PU foam insulation is commonly used in building projects for thermal insulation, rock mineral wool board insulation has better advantages in terms of reusing, recycling, and sustainability. Unlike foam materials, rock mineral wool boards are recyclable. They can be easily removed and reformed into new insulation products or used at another site after building demolition, which will boost the circular economy and waste reduction.

Additionally, on environmental issues, rock mineral wool is produced from available and naturally sourced minerals, such as basalt or diabase, which are renewable sources. Again, foam requires fossil materials to be produced and is considered harmful for the global warming emitted by its use. Furthermore, rock mineral wool is completely non-toxic and doesn’t generate toxic gases or volatile organic compounds during its practice. Foam materials, on the other hand, can release harmful chemicals into the environment.

This information will be included in DPP, as its main purpose is to boost circularity, sustainable development, and closeness in the construction field.

Table 10: Detailed information of Smart Roof Base which proposed to be included in DPP.

Categories	Information
Product Identification	BaseSmartRoof
	Rock mineral wool SmartRoof Base and SmartRoof Thermal are used as a thermal, acoustical and fire insulation product. This EPD has been developed for the most common product sold on the appropriate market.
	DESIGNATION CODE EN 13162:MW-EN 13162-T5-TR7,5-CS(10)30-PL(5)300-WS-WL(P)-MU1
	KNAUFINSULATION
Material Composition and Ingredients	**List of Ingredients: Mineral wool boards (R**enewable Materials) In terms of composition, inorganic rocks are the main components (typically 97%) of stone wool, with a remaining fraction of organic content which is generally a thermosetting resin binder. The binder content is typically less than 4%. The inorganic part is made of volcanic rocks, typically basalt, also dolomite and with an increasing proportion of recycled material in form of slags or briquettes, a mix of stone wool scrap and cement.
	Traceability of Raw Materials: The main raw materials are diabase (a rock that is like volcanic rock basalt), dolomite and briquette. The briquette is made of rock mineral wool waste (internal or external), waste of raw materials and cement. Additionally, coke is also added in the cupola as an energy carrier. Further down the manufacturing line, a binder (thermos set resin) is spread onto the fibres. Then, the polymerization contributes to fix the products dimensions and mechanical properties.
Performance Characteristics	Technical data sheets: https://www.knaufinsulation.pl/produkty/smartroof-base
	Performance testing results: www.dopki.com/R4308LP.
	Expected Lifespan: Reference service life When used correctly, the reference service life of Knauf Insulation rock mineral wool is merely limited by the service life of the components and/or building in which it is incorporated; this is substantiated by current industry findings, for example in case of deconstruction of buildings. As a minimum, we consider a reference service life of 50 years.
	Compliance with Standard and Performance Testing Results: Harmonized Technical Standard EN 13162
Quality Standards	ISO 9001:2008 quality management system
Compliance and Certification	SmartRoof Base boards are CE marked, in accordance with the guidelines of the harmonized standard EN 13162, and have Hygienic Certificate No. 110/322/111/2018)
	OHSAS 18001: 2007 occupational health and safety management system certificate, Energy Management System certificate according to EN ISO 50001: 2011.

Sustainability and Environmental Impact	Life Cycle Assessment (LCA) Summary: Key environmental impact data throughout the product lifecycle, including embodied carbon, resource consumption, and end-of-life options. Recyclability: Details on the product's recyclability, including the type of recycling process it's suitable for and any special considerations Achievement of sustainability certifications like LEED BREEAM. Design for Disassembly: Information on whether the product is designed for easy dismantling to facilitate reuse of components at the end of its lifespan. Remanufacturing Potential: Indicate if the product can be remanufactured back into its original form or a new product at the end of its lifespan. **All above information can be found in:** Environmental Product Declarations - EPDs ENVIRONMENTAL PRODUCT DECLARATION as per ISO 14025 and EN 15804 https://pim.knaufinsulation.com/files/download/epd_smart-roof-base_thermal.pdf
Digital Connectivity	**Integration with Building Information Modelling (BIM).** DESIGNATION CODE EN 13162:MW-EN 13162-T5-TR7,5-CS (10)30-PL(5)300-WS-WL(P)-MU1 **Using this code when define the material during modelling.**

To facilitate the accessibility of complete information about products for all stakeholders, a digital platform with QR code integration will be developed (see Figure 21). IT specialists will design this system, and the most important information about smart roof insulation materials will be easily and quickly accessible on the sites or remotely. QR codes can be printed or displayed on the packaging and product labels, as well as in any documentation. Anyone interested in the specifics about the item's life cycle simply scans the code with their mobile device, and the information immediately becomes available.

Figure 21: Proposed Digital Product Passport for Smart Roof Insulation.

5.4 Challenges in Implementing a Digital Product Passport

In this research and through working on the case study and based on the result of the survey (see Figure 22), several challenges have emerged regarding the implementation of Digital Product Passports (DPPs) for construction products and materials.

One of the main technical challenges is the **absence of standardised data** formats. Construction products and materials come from many manufacturers with different specifications and documentation practices, which makes it difficult to issue a universal digital passport. It is critical to **ensure that the data included in DPPs is accurate and complete**. Otherwise, poor decisions can be made based on the data, and the benefits of DPPs can be nullified.

Another challenge is **stakeholder engagement**, as the successful implementation of DPPs requires buy-in from a range of stakeholders, including manufacturers, suppliers, contractors, and regulators. Ensuring that these parties are engaged and understand the benefits and requirements of DPPs can be difficult. I would also consider **resistance to change** to be a problem; implementing DPPs requires large changes to existing processes and workflows, and while doing so, organisations may encounter resistance from employees who are comfortable with traditional methods.

In addition, deciding who is legally responsible for the accuracy and maintenance of the data in DPPs can be complicated, including manufacturers, suppliers, and perhaps even third-party certifiers. Moreover, competitive concerns are a huge challenge, meaning that companies that refuse to share a great deal of product information, given their fears for their competitors, Hence, the main challenge is to balance transparency with the protection of proprietary information.

However, it is extremely crucial to address these challenges if the full potential of DPPs in the construction industry is to be realized. Overcoming these challenges and successfully implementing DPP for construction products and materials will require continued research, collaboration between all the stakeholders, and the standardisation of frameworks and guidelines.

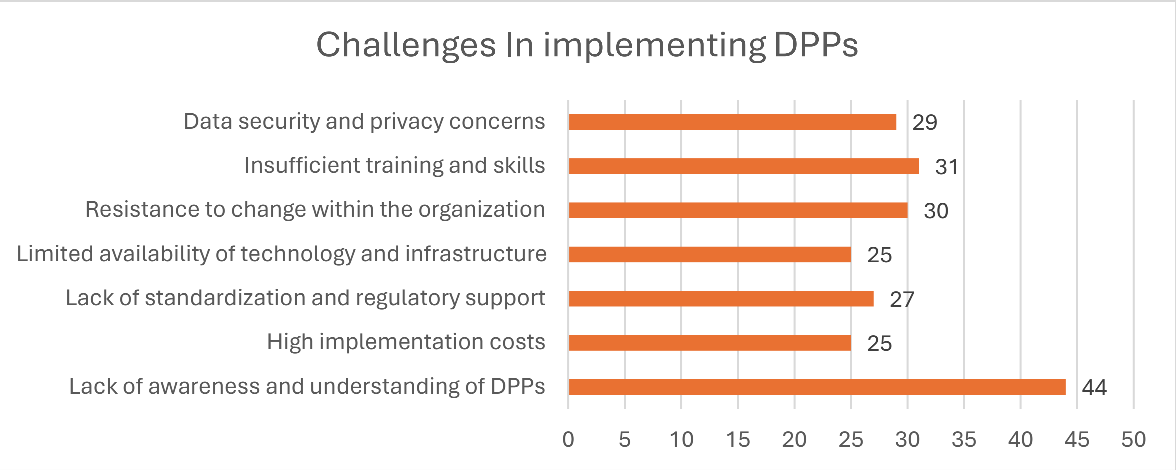

Figure 22: Survey result of the question: What do you perceive as the primary barriers to implementing a DPP in the construction sector?

6. Conclusion and Recommendation for Future Research

The thesis is concluded in this last chapter. It starts with an overview of the main findings and ends with recommendations for further research directions.

6.1 Main Conclusion

The construction industry is facing a big transition by trying to adjust to sustainability and circular economy values. An interesting tool that is starting to attract attention is the Digital Product Passport (DPP), which seeks to provide complete information about products over their entire life cycle. DPPs are designed to improve transparency, traceability, and data management while also supporting sustainable practices and regulatory compliance.

There is a significant amount of scholarly literature related to digital product passports. However, there is a gap in understanding the specific product information that DPPs must contain about the products and what role they play for the products at different stages of their circulation in the circular economy. Therefore, the purpose of this study was to answer the research questions: what information must be placed in DPPs, what advantages there are to DPPs, who will benefit from these advantages, and how the DPPs can be related to BIM technology. Through a comprehensive analysis, including a case study of the Smart Roof Base insulation material by KNAUFINSULATION, several key insights and findings have emerged.

The benefits of DPPs are substantial and multifaceted. Improved traceability of construction materials, and hence quality control as well as safety standards. With DPPs, it is easier to transition to a circular economy, including the practices of reduce, reuse, regenerate, and recycle, which, in turn, results in less waste and reduced resource use. In addition, it is easier to ensure that the DPP data offered will be supportive of compliance with regulations, which is important given the increasingly stringent environmental standards around the world.

Furthermore, the study has provided an insight into what specific information should be included in DPPs to make them more effective. It has been established that the key types of data are as follows: manufacturing details, material composition and ingredients, usage information, end-of-life options, sustainability focus for closed-loop systems, and comprehensive lifecycle data. These data types are critical for the proper evaluation of the product by all stakeholders at all stages, from construction to final deconstruction or recycling.

The research has also highlighted the primary stakeholders who stand to benefit from DPPs, including manufacturers, contractors, architects and designers, facility managers, regulatory bodies, and building owners. Each of these groups relies on accurate and accessible product data to optimise their roles within the construction process, enhance efficiency, and uphold sustainability standards.

However, the implementation of DPPs also entails several challenges. Some of the major challenges include managing the huge collection of data and ensuring the quality of the data. Other major challenges are safeguarding business data and intellectual property and the integration of DPPs with existing digital tools like BIM. Addressing the challenges would require collaborative efforts across the industry and the development of data management systems. The industry also requires some clear guidelines to balance the transparency and protection of business data.

6.2 Recommendations for Further Research Directions

This study concerning Digital Product Passports (DPPs) for construction products and materials shows several areas of research that should be assessed. This subchapter proposes a few recommendations intended to fill the existing gaps and overcome some of the challenges associated with DPPs while exploring future opportunities for improving their implementation and the impact of DPPs on the construction industry.

Further research should focus on developing and promoting standardised forms of data for DPPs. This requires further exploration of the best and most efficient options for enabling interoperability across systems and platforms. Collaborative effort among industry stakeholders, regulatory bodies, and technology providers that can unite to define common standards for broad adoption. Additionally, as construction projects are greatly diversified in terms of size and complexity, DPP systems must be scalable to handle vast amounts of data without significantly compromising performance. The research effort should be focused on scalable architecture designs as well as optimisation techniques to make sure that DPP systems can handle all the requirements and demands posed by small-scale projects and their large-scale counterparts.

Ensuring that DPP systems are compatible with the enormous diversity of software and technologies currently employed in construction is one of the most significant technical challenges. These included project financing and payment software, building information modelling (BIM) systems, procurement platforms, and enterprise resource planning (ERP) systems. This includes research around the development of APIs and other integration mechanisms that can help in the interaction between DPPs and these existing systems.

Efficient data transfer and synchronisation are required between the DPPs and other digital systems. For future research, this study suggests developing strong data exchange protocols that allow all platforms to update in real time while ensuring their accuracy. “ That includes examining cloud-based solutions and decentralised technologies such as blockchain to increase the integrity and security of its data.

Layout of the investigation about customisation of DPPs for different construction product categories Every category of product, be it insulation materials, structural components, or finishes, will have a different set of data requirements and life cycle attributes. Further research should follow in the direction of developing dedicated DPP frameworks that would satisfy such a need. Finally, studies on finding the right balance between transparency without spilling over into compromising business confidentiality and intellectual property. Research efforts should try to develop strategies and technologies that protect privacy and at the same time allow for maintaining business-critical product details open for sustainability and regulatory requirements.

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Appendix I: Survey questions

General Questions:

Q1-What is Your Job Title?

Q-2 Country of Your Organization?

Q3-What part of the construction industry value chain do you represent? Please, choose the one that suits best.

Design and manufacturing (e.g. architect, engineer, designer, product manufacturer)

Construction (e.g. general contractor, subcontractor, builder) o R&D and strategy (e.g. researcher, business analyst, consultant, strategic planner)

End-of-life management (e.g. demolition contractor, waste management, recycling)

Government and policy bodies (e.g. regulatory agencies, inspector, planning official, safety & health administration)

Others

Q4-please indicate the type of construction you are dealing with?

Commercial

Residential

Industrial

Government-owned

Institutional

Other

About Digital Product Passport (DPPs)

Q5-Is circular economy (CE) or sustainable development a part of your organization's plan?

1-Yes

2- No

Q6-How familiar are you with Digital Product Passports (DPPs) for construction products and materials?

Very Familiar

Somewhat familiar

Not familiar at all

Q7-How do you think it is important for construction products and materials to have standardized digital passports containing information on environmental impact, performance, and characteristics?

Very Important

Somewhat important

Not important

Q8-How likely are you to adopt DPPs for construction products and materials in your future projects?

Very likely

Somewhat likely

Not likely

Q9-How do you think the adoption of DPPs would impact your organization's sustainability practices?

Positively

Negatively

No impact

Q-10 In your opinion, which of the following construction product supply chains would benefit the most from a Digital Product Passport (DPP) in terms of circularity purposes? Please select up to 3 options.

Concrete products (e.g. beams, columns, slabs, foundations)

Metal products (e.g. beams, bars, sheets)

Timber and other wooden products (e.g. plywood panels, chipboards)

Plastic products (e.g. tubes, pipes, water barriers)

Bricks, tiles, ceramics

Aggregates and Asphalt

Insulation (including both mineral and non-mineral thermal insulation)

Doors and windows

Wall systems

Roofing and flooring systems

Q11-On a scale of 1 to 5, how well do you think DPPs will address the current information gaps and challenges in the construction industry?

Q12- On a scale of 1 to 5. How would you rate the level of collaboration and information sharing among stakeholders in the construction supply chain?

Benefits of a Digital Product Passport (DPPs) for Construction Product

Q13-On a scale of 1 to 5. To what extent do you believe DPPs will improve the Transparency and Traceability of product information?

Q14- On a scale of 1 to 5. To what extent do you believe DPPs will encourage sustainable practices in the construction industry?

Q15- On a scale of 1 to 5. To what extent do you believe DPPs will give value for reuse, regeneration, recycling of construction product?

Q16- On a scale of 1 to 5. To what extent do you believe DPPs will Improve Closed Circuit or Closed loop in construction sector?

Q17-On a scale from 1 to 5, how much do you believe Digital Product Passports (DPPs) will help in reducing costs for construction projects?

Q18-On a scale from 1 to 5, how much do you believe Digital Product Passports (DPPs) will help in Improving Time Management for construction Project?

Q19-On a scale of 1 to 5, to what extent do you believe that Digital Product Passports (DPPs) will enhance quality improvement for construction projects?

Q20-On a scale from 1 to 5, how much do you believe that Digital Product Passports (DPPs) will help reduce information overload for construction teams?

Q21- On a scale from 1 to 5, how much do you believe that Digital Product Passports (DPPs) will facilitate collaboration within project teams?

Q22 On a scale from 1 to 5, how much do you believe that Digital Product Passports (DPPs) will reduce Risk of Errors and Rework during the construction process?

Q23- On a scale from 1 to 5, how much do you believe that Digital Product Passports (DPPs) will facilitates planning and procurement for construction product?

Barriers in Implementing Digital Product Passport (DPPs) in the construction sector.

Q24-What do you perceive as the primary barriers to implementing a DPP in the construction sector? (Select all that apply)

Lack of awareness and understanding of DPPs

High implementation costs

Lack of standardization and regulatory support

Limited availability of technology and infrastructure

Resistance to change within the organization.

Insufficient training and skills

Data security and privacy concerns

Q25- To what extent do you agree with the following statement: "Our organization has the necessary technology and infrastructure to support the implementation of DPPs."

Q26- How significant are cost-related barriers to implementing DPPs in your organization?

Q27- To what extent does resistance to change within your organization affect the adoption of DPPs?

Q28- How concerned are you about data security and privacy in relation to DPPs?

Information Inclusion in Digital Product Passport (DPPs) for Construction Product.

Q-29 Which of the following types of information do you think should be included in DPPs for construction products? (Select all that apply)

Technical specifications (e.g., thermal conductivity, fire resistance)

Material composition (e.g., ingredients, recycled content)

Environmental impact (e.g., embodied carbon, life cycle assessment)

Manufacturing process (e.g., production methods, energy use)

Regulatory compliance (e.g., certifications, standards met)

End-of-life options (e.g., recyclability, disposal methods)

Product Identification, Installation Guidelines, Geometrical Information, Health and Safety

Appendix II: Interview Question

The guide included the following key sections and questions:

General Background

Q1-Can you please introduce yourself and describe your role within your organization?

Q2-How long have you been involved in the construction industry?

Q3-What experience do you have with sustainability practices and circular economy principles in construction?

Understanding of Digital Product Passports (DPPs)

Q4-What is your understanding of Digital Product Passports (DPPs)?

Q5-Have you or your organization used or implemented DPPs in any of your projects? If so, could you describe your experience?

Benefits of DPPs

Q6-What do you believe are the key benefits of implementing DPPs in the construction industry?

Q7-How do you think DPPs can enhance traceability and quality control in construction projects?

Q8-In what ways can DPPs facilitate circular economy practices, such as the reuse and recycling of materials?

Q9-How might DPPs improve regulatory compliance and adherence to environmental standards?

Data Requirements

Q10-What types of information and data do you think should be included in a DPP for construction materials?

Q11-How important is it to include manufacturing, usage, end-of-life, and lifecycle data in DPPs?

Q12-Are there any other specific data points you believe are critical for DPPs to be effective?

Stakeholders and Their Roles

Q13-Which stakeholders do you think will benefit the most from the implementation of DPPs in the construction industry?

Q14-What roles do manufacturers, contractors, facility managers, and regulatory bodies play in the successful implementation of DPPs?

Q15-How do you see end-users or building occupants benefiting from DPPs?

Challenges and Barriers

Q16-What do you perceive as the main challenges or barriers to implementing DPPs in the construction industry?

Q17-How do you think issues of business confidentiality and protection of intellectual property can be managed in the context of DPPs?

Q18-What are the challenges related to ensuring the quality and accuracy of the data included in DPPs?

Integration with BIM Technology

Q19-Do you see potential benefits in integrating DPPs with Building Information Modelling (BIM) technology? If so, what are they?

Q20-What challenges do you foresee in integrating DPPs with existing digital tools and systems like BIM?

Closing Questions:

Q21-Do you have any additional comments or insights on the topic of DPPs?

Q22-Are there any other aspects of DPPs you think are important to discuss that we haven't covered?