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Digital product passports for construction products

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Abstract

To accelerate the transition to a circular economy in the construction sector, the digital product passport has been proposed as a tool for traceability. It collects data on all life cycle phases of a products, and shares it across the entire value chain. Despite the presumed implication of a digital product passport for circularity, there are some notable gaps in literature, particularly within the construction industry.

In this thesis, three research objectives were formulated. Firstly, the benefits of a digital product passport are explored. Secondly, the data needs of key stakeholders for a digital product passport are identified, to fully understand its potential. Thirdly, the barriers and challenges in implementing the digital product passport are recognized. To fulfil the objectives, a qualitative approach was chosen to gain a more holistic understanding of a phenomena that is still emerging. Semi-structured interviews and a survey were conducted.

Several benefits were identified which stem from enhanced traceability, and are connected to different stages of a product's life cycle. From improved resource efficiency to facilitated decision-making, accessible information retrieval and improved data management, the findings emphasize the role of the digital product passport in transforming to a circular economy. To ensure that the digital product passport is beneficial, the identified required contents include manufacturing, usage, end-of-life and life-cycle data. The main barrier that could impede successful implementation of the tool include business confidentiality issues, such as protecting intellectual property. Other challenges involve ensuring data quality, for instance, keeping the information up to date.

The findings suggest that the identified data types may function as a foundational framework. Future research should further refine the framework by determining precise data of each data type. Moreover, the study indicates that the data content of a digital product passport should be tailored to each product group. Herein, an optimal level of detail that adheres to intellectual property while ensuring transparency needs to be found.

Keywords Digital product passport, circular economy, traceability, construction products

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Sammandrag

För att påskynda övergången till en cirkulär ekonomi inom byggsektorn har det digitala produktpasset föreslagits som ett verktyg för spårbarhet. Det samlar in data om alla faser i en produkts livscykel och delar över till hela värdekedjan. Trots den förmodade betydelsen av ett digitalt produktpass för cirkuläritet, förekommer det betydande luckor i litteraturen, särskilt inom byggbranschen.

Denna avhandling formulerar tre forskningsmål. Det första målet är att undersöka fördelarna med ett digitalt produktpass. Det andra målet är att identifiera intressenters databehov för ett digitalt produktpass, med avsikten att förstå dess potential till fullo. Det tredje målet är att identifiera hinder och utmaningar i implementeringen av det digitala produktpasset. För att uppfylla målen valdes en kvalitativ metod avsedd att skapa en överblick över ett fenomen som fortfarande håller på att utvecklas. Semistrukturerade intervjuer och en enkät genomfördes.

Flera fördelar som härrör från förbättrad spårbarhet identifierades och de kan kopplas till olika faser av en produkts livscykel, allt från förbättrad resurseffektivitet till underlättat beslutsfattande, enkel informationssökning och förbättrad datahantering. Dessa resultat betonar det digitala produktpassets roll i övergången till en cirkulär ekonomi. För att säkerställa det digitala produktpassets nytta identifierades tillverknings-, förbruknings-, livscykels- och uttjäningsdata som nödvändiga datagrupper. Det främsta hindret för lyckad implementering kopplades till frågor gällande affärssekretess, till exempel skydd av immateriella rättigheter. Andra utmaningar handlar om att säkerställa datakvaliteten, såsom att hålla informationen uppdaterad.

Resultaten tyder på att de identifierade datagrupperna kan fungera som ett grundläggande ramverk. Framtida forskning bör ytterligare förfina ramverket genom att fastställa exakta data för varje datagrupp. Dessutom indikerar resultaten att datainnehållet i ett digitalt produktpass bör skräddarsys för varje produktgrupp. Här bör man hitta en optimal detaljnivå som respekterar immateriella rättigheter och samtidigt säkerställer öppenhet.

Nyckelord Digitala produktpass, cirkulär ekonomi, spårbarhet, byggprodukter

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Preface and acknowledgements

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Abbreviations

CDW	construction and demolition waste
CEAP	Circular Economy Action Plan
CPR	Construction Products Regulation
DoP	declarations of performance
DPP	digital product passport
EPD	environmental product declaration
EPR	extended producer responsibility
ESPR	ecodesign for sustainable products regulation
EU	European Union
GDPR	General Data Protection Regulation
IoT	internet of things
JSON-LD	JavaScript Object Notation for Linked Data
QR	quick response
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RFID	radio-frequency identification
SMEs	small and medium-sized enterprises
SPI	sustainable products initiative

1 Introduction

The construction sector is responsible for using 40 % of all extracted materials, producing one third of total carbon dioxide emissions as well as generating 40 % of the total waste produced globally (Heinrich & Lang, 2019). Currently, the construction sector follows a linear economy model characterized by the ‘take-make-dispose’ approach, prominently designed for economic profitability. Raw materials are extracted, made into products, and once used, disposed. Moreover, the world population is projected to reach 9,8 billion by 2050, of which approximately two-thirds is estimated to live in urban areas (United Nations, 2019). Additionally, by 2050, it is predicted there will be an increase of 2,4 billion new residents in the cities of developing countries (United Nations, 2019). Consequently, this creates demand for housing with a subsequent increase in construction activities.

Due to the current prevailing unsustainable linear economy model, the ever-growing population and rapid urbanization, there is a growing need to transform into a circular economy to attain the sustainable development goals declared by the United Nations (2015). A circular economy is characterized by its restorative and regenerative nature, where the aim is to extend and intensify resource loops, as well as to recirculate the resources back into the system after use. Such life-extending strategies involve, for instance, reuse, repair, and recycle (Bocken et al., 2016). Even though the construction industry accounts for substantial amounts of negative impacts, the industry is also concurrently acknowledged in having the highest potential in the transition to a circular economy (Hossain et al., 2020).

Several enablers are recognized to accelerate the transition to a circular economy, of which traceability and digitalization techniques are considered key aspects (Santana & Ribeiro, 2022; Chauhan et al., 2022). A digital product passport (DPP) is a digital tool that provides traceability of a product by collecting and storing data of a product, and sharing it with the entire value chain (Koppelaar et al., 2023; Navarro et al., 2022). Indeed, the ultimate goal of a DPP is to promote circularity as a result of closing information gaps across the value chain (Ducuing & Reich, 2023). The tool aims to, for instance, foster circular economy practices, facilitate circular design, save resources, avoid greenwashing and enable better decision-making (Götz et al., 2022; Plociennik et al., 2022b). The initiative of developing a DPP is rooted in the Sustainable Product Initiative (SPI) presented by the European Commission (2021), as a part of achieving the goals set by the EU Green Deal (European Commission, 2019a). Moreover, it is also included in the revised version of the Construction Products Regulation (CPR) (European Commission, 2022b).

Despite the presumed significance of DPPs for circularity, there are some significant literature gaps. DPP is yet an emerging tool, with limited research focused on the construction industry. Another main gap is the lack of a standardized framework, regarding e.g. data content, format, storage and interoperability (Galatola, 2022; Walden et al., 2021). Consequently, there is a need to explore the data needs of each actor in the construction industry to materialize the contents of a DPP (Jensen et al., 2023), not only to fully understand the potential and benefits but also to ensure that a DPP will be widely adopted, useful and effective in the long run. Moreover, challenges and barriers need to be identified to ensure the realization of potential benefits (Jensen et al., 2023), and to identify any other possible gaps.

To fill these gaps, the main research objective of this thesis is to explore the benefits of a DPP for key stakeholders in the construction industry. The aim is to identify key stakeholder's data needs of a DPP to fully understand its potential. Another aim of this thesis is to identify the barriers and challenges in implementing a DPP, that could act as a bottleneck in reaching its full potential. Herein, the aim is also to recognize the conditions for a DPP. To fulfil these objectives, the following research questions are formulated:

RQ1: What are the benefits of a digital product passport for key stakeholders in the construction industry?
RQ2: What are the data requirements for a digital product passport for construction products?
RQ3: What are the barriers and challenges in implementing a digital product passport for construction products?

To answer the research questions, semi-structured interviews and a survey were used as research methods. The scope of this thesis is focused on new construction products, thus, excluding recycled construction products, as these can have a long lifespan and some aspects cannot be known until far into the future, e.g. recycling aspect, prices and impacts (Götz et al., 2022). Moreover, the focus will be specifically on construction products, rather than buildings or larger complex structures. This thesis also sets its limitations to focus on the DPP as a tool, and will not delve into the DPP system, i.e. the technical aspects or the underlying IT-infrastructure. As the thesis is funded by an EU-project (ICEBERG), the geographical scope is set to the EU-area.

The thesis consists of a background study, methodology, results, discussions and conclusions. In the background, the theoretical framework of the thesis is formed. The methodology describes the experimental part, that aims to answer the research questions. Then, results and discussion interpret and analyze the results obtained in the experimental part. Finally, the thesis is concluded, with suggestions for future research.

2 Background

This background study aims to present the theoretical framework for the thesis and to provide the foundational groundwork for the methodology. In order to understand the importance of a DPP for construction products, this section first presents the concept and principles of circular economy. Then, the current situation regarding circularity in the construction industry is reviewed. Finally, DPPs are presented in terms of its concept, state-of-art review as well as recognized data requirements, benefits and challenges in implementation.

2.1 Circular economy in the construction industry

This subchapter describes the fundamental idea of circular economy as a concept. The framework and its principles are reviewed in order to understand its context for the thesis. Then, circularity in the construction industry is briefly reviewed. Finally, an overview of transparency and traceability as well as the role of data for circularity is presented, underlining the importance and need for digital technologies, such as a DPP.

2.1.1 The concept of circular economy

Circular economy is defined as an "*economic system that uses a systemic approach to maintain a circular flow of resources, by recovering, retaining or adding to their value, while contributing to sustainable development*" (International Organization for Standardization, 2023). Typically, circular economy is conceptualized as an umbrella concept encompassing various resource life-extending strategies (Blomsma & Brennan, 2017), however, the fundamental objective of circular economy can simply be described as an economic model with a regenerative nature based on the principles of closed loops (Lieder & Rashid, 2016). A more comprehensive way to approach the resource loops is the thinking of slowing, narrowing and closing loops. In here, the idea is to extend and intensify the use of resources (slowing), reduce the number of resources used per product (narrowing), and recirculate the resources back into the system (closing) (Bocken et al., 2016). The concept of circular economy can further be understood by contrasting it with its antonym, linear economy. Linear economy is the current prevailing economic model, where value chains have a 'take-make-dispose' construct and is prominently based on financial objectives as well as using design to promote high consumption rates (Bocken et al., 2016). While linear economy can be a conventional system from the economic feasibility point of view, it has been shown to be highly unsustainable, causing issues from the social, economic and environmental point of views (Bocken et al., 2016). Consequently, this has resulted in a paradigm shift towards circular economy (Rajput & Singh, 2019).

Even though circular economy has gained a lot of attraction during the recent years (Ghisellini et al., 2016), the concept is not entirely novel, as its roots can be traced back all the way to 1870s (Tuladhar et al., 2022). Some significant works have contributed to the evolution of the concept over time, for example, Stahels work (1982) introduced the underlying idea of economy in loops, underlining the optimization of the use of manufactured objects as the core of circular economy. Correspondingly, it is a characteristic that distinguishes circular economy from linear economy. Braungart & McDonough (2002) further developed this idea with the holistic strategy that is the cradle-to-cradle principle, where closing the resource loops occurs in two different cycles. Herein, products are designed to undergo multiple life cycles, and once the product has reached its end of the use phase, it will continue either in a biological or technological cycle. The biological cycle comprises of materials that can be reintroduced to the biosphere through processes, whereas technological cycles include materials that are not naturally generated in the biological cycle (Ellen MacArthur Foundation, 2019). This approach can be visualized as a butterfly diagram, see Figure 1.

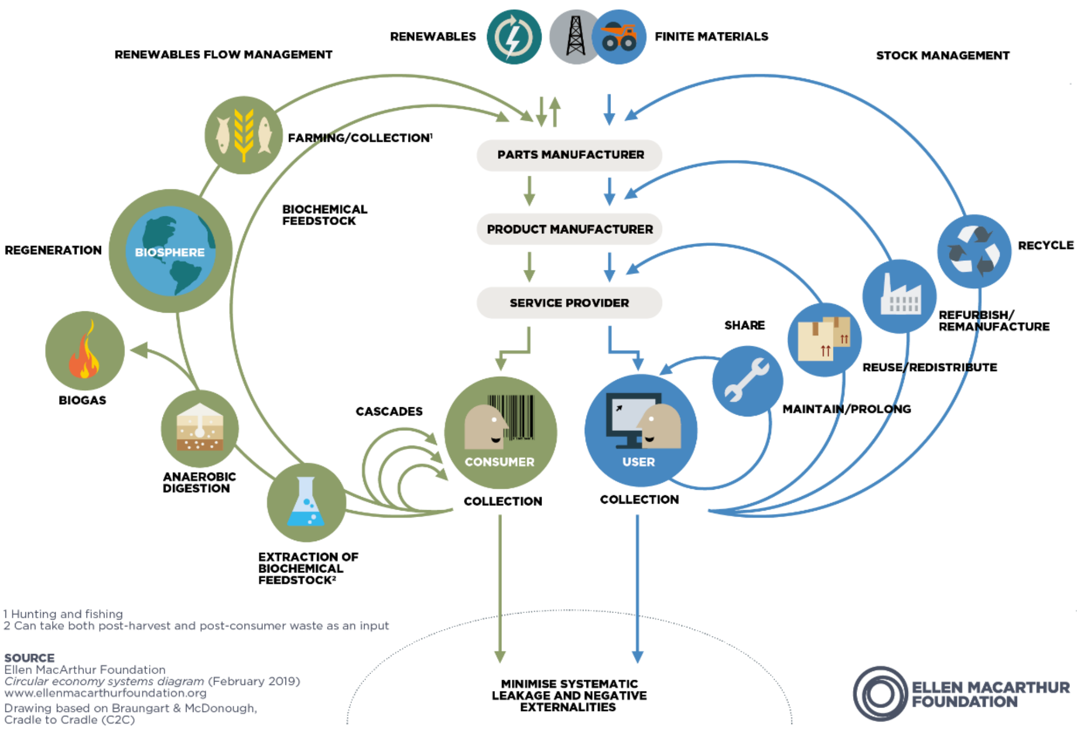

Figure 1. Butterfly diagram (Ellen MacArthur Foundation, 2019).

At present, it can be stated that the circular economy concept has risen in prominence during the last decade (Chauhan et al., 2022; Ghisellini et al., 2016), both in academia and from government bodies (Geissdoerfer et al., 2017). The EU published the first Circular Economy Action Plan in 2015 (CEAP) (European Commission, 2015), one of the main pillars of the European Green Deal (European Commission, 2019a). Herein, it is stated that circularity is a key building block to address the existing environmental, economic and social issues. A new revised version of the CEAP was published in 2020 (European Commission, 2020), providing a more extensive framework with the objective of making sustainable products the new standard, reducing the amount of waste and effectively implement circularity for people, regions and cities. Moreover, the focus is on resource-intensive sectors, of which the construction industry is acknowledged as one.

2.1.2 Core principles of circular economy

Kirchherr et al. (2017) distinguishes in their review two core principles of circular economy. The first core principle is related to the R-framework, which conceptualizes the elements of circular economy as circular strategies and operates as a guiding principle for systematic circular thinking. While there is no single universally accepted framework, three frameworks are prominent: the 3R-, 4R- and 9R-framework. The original framework, 3R, incorporates the pillars of *Reduce*, *Reuse* and *Recycle*, and is seen as the founding core principle for circular economy (Ghisellini et al., 2016). The 4R- framework further adds *Recover* to the same list, which is the core of the Waste Framework Directive at EU (European Commission, 2008). The most extensive framework, 9R, further incorporates *Refuse*, *Rethink*, *Repair*, *Refurbish*, *Remanufacture* and *Repurpose,* see Figure 2. Moreover, 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 ranked with a lower number is preferred, as it has greater circular benefits as fewer resources are required to produce new materials. The idea behind circular strategies R0-R2 is based on a smart product use and manufacture, R3-R7 involve extending the lifespan of products and it parts, whereas R8-R9 involve a useful application of materials (Potting et al., 2017).

Circular economy	Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or use a different product
		R1 Rethink	Make product use more intensive, e.g. by sharing or multifunctional products
		R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer resources or materials
	Extend lifespand of product and its parts	R3 Reuse	Reuse a product discarded by another consumer
		R4 Repair	Repair and maintenance of a product's defects to its original function
Higher circularity		R5 Refurbish	Restore an old product to bring it up to date
		R6 Remanufacture	Use parts discarded product in a new product with the same function
		R7 Repurpose	Use parts of a discarded product in a new product with a different function
	Useful application of materials	R8 Recycle	Process materials to obtain materials with the same or lower quality
Linear economy		R9 Recover	Incineration of materials with energy recovery

Figure 2. The 9R-framework (adapted from Potting et al., 2017).

The second core principle highlights the need for systemic change, indicating that the transition to a circular economy requires effort from actors at three levels: micro-, meso- and macrosystems (Kirchherr et al., 2017). Change at each level is necessary for the transition to be effective (Fang et al., 2007; Jackson et al., 2014). The systemic change in the micro-system requires efforts from companies, consumers and at product level, whereas the meso-system calls for changes in collaboration between companies and industrial networks (Kirchherr et al., 2017; Vanhamäki et al., 2019). Finally, the systemic change on the macro-level requires policy changes on a national and a regional level, focusing on adjusting the structure of the entire economy model (Kirchherr et al., 2017; Vanhamäki et al., 2019).

2.1.3 Circularity in the construction industry

Currently, the construction sector follows the traditional linear economy model and is highly unsustainable (Mangialardo & Micelli, 2018). The industry is one of the most resource-intensive sectors, that is responsible for using two-fifths of all extracted material resources by mass, producing one third of the total carbon dioxide emissions (Heinrich & Lang, 2019) and generating the largest percentage (40 %) of all waste produced in the world (Akanbi et al., 2018). On the other hand, the positive impacts of the construction industry are associated with its contribution to GDP, employment opportunities as well as producing various buildings and constructions that meets the need of its users (Smol et al., 2015).

There is a limited amount of research done on implementing the principles of circular economy in the construction industry, compared to other industries producing short- and medium-lived products (Adams et al., 2017). The slow adaptation of circular economy principles can be explained by the lack of a comprehensive approach throughout the supply chain, the low value of most construction products at their end-of-life, short-term perspectives (Adams et al., 2017), the complexity of structures and supply chains, as well as the uniqueness of projects, that require more time for innovations (Pomponi & Moncaster, 2017). Nevertheless, the construction industry is regarded to have the highest potential in transforming into a circular economy (Hossain et al., 2020).

Currently, the focus of research has been on end-of-pipe solutions for managing waste, resulting in an improvement in the management of construction and demolition waste (CDW) (Adams et al., 2017). Half of all the waste produced due to construction arise from end-of-life activities, particularly in demolition, as buildings are typically discarded at the end of their use-phase (Akanbi et al., 2018; Benachio et al., 2020). However, most of the research focus on recycling practices of CDW, not reusing (Adams et al., 2017). Less than one-third of CDW is recycled or reused, and the rest is discarded, consisting mainly of lumber, asphalt and concrete (World Economic Forum, 2016). The retrieved waste from CDW is, however, mostly downcycled with decrease in value, functionality and quality, as opposed to the principles of circular economy (Adams et al., 2017). According to the circular economy principles, the CDW should be reused with their components deconstructed, in order to become material banks for new buildings, retaining the materials in a closed loop (Hopkinson et al., 2019). Nevertheless, there is a need for developing and implementing circular practices in earlier phases prior to end-of-life (Adams et al., 2017), as well as new ways to design structures and buildings in order to facilitate the disassembly for reuse and adaptation (Hopkinson et al., 2019). The circular economy practices can be associated with the five life cycle stages of a building: (i) design, (ii) manufacture and supply, (iii) construction, (iv) use-phase and refurbishment, and (v) end-of-life, see Table 1 (Adams et al., 2017; Benachio et al., 2020).

Table 1. Circular economy practices for each life cycle stage (Adams et al. 2017; Benachio et al. 2020).

Life cycle stage	Circular economy practices
Design	Design for disassembly Design for adaptability and flexibility Design out waste Design and use of modular buildings Specify reclaimed and recycled materials Analyze the reuse potential of materials through a simulation in a BIM model Life-cycle analysis to identify the benefits of reusing different materials in the design stage Material stock data Use of a scale for assessing the extent of the implementation of circular economy practices within a company
Manufacture and supply	Eco-design principles Increase the lifespan Reduce use of materials Reduce use of hazardous materials Reuse of secondary materials Repurpose materials Design for disassembly of products Design for product standardization Reverse logistics Take-back schemes Development of DPPs
Construction	Reuse of products in new constructions Reduce the waste Procure reused or recycled materials Off-site construction
Use-phase and refurbishment	Reduce the waste Maintenance and repair Adaptability Flexibility
End-of-life	Selective demolition Deconstruction Reuse of products and components Management of CDW Closed-loop and open-loop recycling

2.1.4 Construction products

Construction products encompass a wide range of products, systems and materials. These involve, for instance, wooden products, steel structures, concrete, plastics, as well as multimaterial systems such as wall systems and façade systems. These construction products can be more specifically categorized, as shown in Table 2. (Rakennustieto, 2013)

Table 2. Construction product categories with examples (adapted from Rakennustieto, 2013).

Construction product category	Examples
Concrete products	Beams, columns, slabs, foundations
Timber and other wooden products	Cross-laminated timber, cladding, plywood panels, chipboards
Metal products	Beams, bars, tubes, sheets, mesh
Plastic products	Tubes, pipes, water barriers
Bricks, tiles, ceramics	Clay bricks, porcelain tiles, ceramic bricks
Aggregates	Gravel, stone, sand
Mineral and non-mineral thermal insulation	Mineral wool, stone wool, expanded polystyrene (EPS), polyurethane (PU)
Doors and windows	Multimaterial systems including materials such as glass, wood, aluminium
Wall systems	Multimaterial systems including materials such as concrete, masonry, gypsum
Roofing and flooring systems	Vinyl floors, carpet tiles, laminates
Interior products that are normally stripped out before demolition	Heating, ventilation and air conditioning (HVAC), radiators

2.1.5 Traceability and transparency

Traceability refers to identifying and tracing the whole value chain of a product, providing information of its history, distribution, location as well as applications of products, materials, parts, and services (International Organization for Standardization, 2015). A traceability system, for example a DPP, supports both tracking and tracing, providing data and information about a product (Santana & Ribeiro, 2022). Transparency, on the other hand, communicates this product information in an accessible way to both internal and external observers (Centobelli et al., 2022). Thus, traceability relies on transparency. Both traceability and transparency are highly crucial in a circular economy, due to the requirements in collaboration, communication and coordination between stakeholders (Santana & Ribeiro, 2022). Furthermore, transparency is a fundamental parameter in the assessment of the supply chain's performance (Centobelli et al., 2022). Implementing circular economy principles can be accelerated through addressing supply chain issues such as monitoring material flows, traceability and collaboration (Rejeb et al., 2023). Thus, the lack of traceability can function as a bottleneck in transforming into a circular economy. The challenge lies in bridging the traceability gap of the value chain, as defining certain variables, e.g. origin, is demanding owing to the complexity of the supply chains and product flows (Centobelli et al., 2022).

In the context of the construction industry, the number of studies on traceability are rather limited. Most notably, the role of traceability in enhancing the circularity of construction products is not well understood. Existing literature mostly cover specific aspects of traceability, such as a specific digital technology, instead of reviewing the traceability for the product's entire life cycle. Compared to other industries, the construction industry is slower in implementing these systems, due to the fragmented nature, complexity, long lifespan of products and the high number of stakeholders involved. (Davari et al., 2023)

2.1.6 The role of data and digitalization for circularity

The synergy between circular economy and digitalization, i.e. smart circular economy, has recently attracted great attention in research (Luoma et al., 2022a; Kristoffersen et al., 2020). Data is recognized as an enabler and a catalyst for a successful transition to a circular economy model in the CEAP (European Commission 2020), moreover, digitalization is identified as an important tool in circular economy (Antikainen et al., 2018). However, data discrepancies currently act as a bottleneck in the transition to a circular economy (Rajput & Singh, 2019), as one of the greatest barriers is the hindered data flow across the value chains, inhibiting traceability (Hedberg & Šipka, 2021). Thus, it is of uttermost importance to recognize the data gap for effective transition to a circular economy (Acerbi & Taisch, 2020).

The associated circularity data is diverse and can provide information for actors and industries on material flows, product lifetime, associated value and environmental impacts (Luoma et al., 2022a). Moreover, this data can be applied to optimize environmental performances of value chains (Luoma et al., 2022a). However, a more efficient utilization and management of circularity data requires appropriate information and technological systems (Luoma et al., 2022a), where digital technologies are regarded as essential for this purpose (Kristoffersen et al., 2020). Digital technologies act as the bridge between data and digitalization, transforming theoretical circular economy principles into viable and practical measures (Chauhan et al., 2022) through, for instance, enabling the monitoring and optimization of product performances (Rusch et al., 2022). In the CEAP, four types of digital technologies are mentioned as contributors to a circular economy: internet of things (IoT), artificial intelligence (AI), big data and blockchain (European Commission, 2020).

Incorporating digital technologies across the supply and value chains involves tracking and tracing of materials and products (Hedberg & Šipka, 2021). Digital technologies can address existing key operational barriers across the value chains (Kristoffersen et al., 2021), and are anticipated to create space for new innovative business models (Chauhan et al., 2022). Additionally, digital technologies can aid in improving the design of products and manufacturing processes, usage of products and waste management (Hedberg & Šipka, 2021). They also have the benefit of informing and educating both consumers and investors, correspondingly, encouraging consumers to be more active participants in the transition to a circular economy (Piscicelli, 2023).

However, digital technologies are still emerging, and there is a lack of effective applications of these for circularity purposes (Kristoffersen et al., 2020). Research that assesses the environmental, economic, and social impact of a smart circular economy is yet scarce and scattered (Piscicelli, 2023). The challenges of digitalizing a circular economy can be connected to various aspects that slow down the transformation of business models. The supply chain requires a common reporting standard and database, as there is a lack of a standardized framework for data collection and sharing throughout the value chain (Acerbi & Taisch, 2020; Hedberg & Šipka, 2021; Kristoffersen et al., 2021), as well as a consensus on common definitions, methodologies and directives on utilizing data (Luoma et al., 2022b). Also, the lack of knowledge and skills is slowing down the transformation (Hedberg & Šipka, 2021). Furthermore, there is little research on the collaborative practices and systems of applying information assets (Rajala et al., 2018). One important aspect in information sharing in circular economy is the motivation of doing so, which is achieved by generating trust and ensuring that the information is not misused (Jäger-Roschko & Petersen, 2022). The need for trust between stakeholders is usually an ignored aspect, however, it is a fundamental part of collaboration (Rajala et al., 2018; Serna-Guerrero et al., 2022). Moreover, the collaboration should be useful and beneficial for all parts involved (Jäger-Roschko & Petersen, 2022).

2.2 Digital product passports

In this subchapter, the concept of a DPP is first reviewed. Then, the end-users of the DPP are presented. Next, the identified benefits and challenges associated with implementing a DPP are reviewed. Finally, the data requirements for a DPP are presented.

2.2.1 The concept of a digital product passport

A digital product passport (DPP) is a tool that contains a set of digital data that provides information on all life cycle phases of a product (Koppelaar et al., 2023). The aim is to track the history of a product in terms of origin, composition, repair and waste management at end-of-life (Götz et al., 2022). Each actor in the supply chain will have access to relevant information on operating or using the product (Navarro et al., 2022), while eventually also adding data to the DPP during the products life cycle (Koppelaar et al., 2023). Currently, studies related to utilizing data for transforming into a circular economy has usually focused on a single strategy, instead of strategies considering the entire value chain (Acerbi & Taisch, 2020). DPPs have the capacity to address the whole value chain, as well as functioning as a connecting element between stakeholders. The ultimate goal of a DPP is to promote circularity by closing information gaps in the value chain through data sharing (Ducuing & Reich, 2023).

First, it is important to differentiate DPP and a DPP system. A DPP is the tool that consists of data provided by actors in the value chain. In contrast, a DPP system refers to the underlying IT-infrastructure that enables the access to the content by facilitating the cross-sectoral interaction, and the assignment of a product to the tool. (Jansen et al., 2023)

A DPP can either be singular, which is linked to a single product (e.g. an unique identity or a serial number), or plural in terms of a set of items (a model, a batch) (Navarro et al., 2022). Furthermore, the variants of DPP can be dynamic and/or static (Walden et al., 2021). A dynamic DPP can be read and modified by actors during use, whereas a static DPP is unmodifiable and can only be read (Plociennik et al., 2022a). Combining both static and dynamic characteristics in a DPP enables certain actors to write data inputs, whereas other actors can only access the DPP and read the data in it (Walden et al., 2021).

The data of a DPP needs to be stored in a system, either in a centralized or a decentralized data storage system (Cura et al., 2022). Centralized data storages have a single owner, and other users are able to access it but not modify it (Cura et al., 2022). Decentralized systems have several owners, with all users having access to the same data (Cura et al., 2022). According to Götz et al. (2022), a decentralized storage system is preferred over centralized storage systems by most businesses. Digitalization techniques such as blockchain technology and internet of things (IoT) have been proposed as data storage systems for DPPs (Walden et al., 2021). Especially blockchain technology has gained great attention lately in the context of DPPs (Jansen et al., 2022), due to its distributed and decentralized database structure, offering transparency, reliability and verifiability (Meva, 2018; Tezel et al., 2020).

The DPP should be accessible in both a machine-readable format (for example JSON-LD, a data interchange format for encoding structured data) as well as a human-readable format (for example PDF or HTML) (Navarro et al., 2022). Furthermore, the DPP should be accessible both through online and offline access points with a universal product identifier, that is linked to a unique internet identification system, e.g. web address (Koppelaar et al., 2023). When a product has been assigned a location on the internet, the data can be accessed in the format of a DPP (Koppelaar et al., 2023). End-users access the DPP with the help of data carriers, which are machine-readable physical tags on the product, such as QR-codes or RFID-tags (Navarro et al., 2022), acting as the link between the physical product and the stored data (Piétron et al., 2023).

The initiative of developing a DPP is rooted in the Sustainable Product Initiative (SPI) presented in 2021, by the European Commission. Furthermore, the Ecodesign for Sustainable Products Regulation (ESPR) legislation presented by the European Commission instituted the framework for DPP (European Commission, 2022). DPPs are also recognized in the EU Green Deal (European Commission, 2019a), EU Battery regulation (European Commission, 2019b), the European data space for smart circular applications (European Commission, 2020), EU Strategy for Sustainable and Circular Textiles (European Commission, 2022a) and in initiatives such as the European Battery Alliance (InnoEnergy, 2023) and the Global Battery Alliance (Global Battery Alliance, 2023). DPPs are aimed to be implemented for various product groups in the future, prioritizing critical product groups such as textiles, batteries and ICT, with construction products to follow.

2.2.2 End-users of a digital product passport

The DPP is intended to be used by various end-users throughout the value chain. Plociennik et al. (2022b) define in their review a simplification of several end-users of a non-industry-specific DPP, based on the source of the information. Two types of actors are identified: material-flow related actors and strategy-oriented actors. The material flow related actors are directly linked with the material flow and its processes, and the following stakeholders are considered:

i) raw material suppliers,
ii) manufacturers,
iii) retailers,
iv) consumers,
v) logistic providers,
vi) repair providers, sorters and recyclers,
vii) waste management actors.

The strategy-oriented actors access material flow data for decision-making and developing strategies. Moreover, they contribute with information related to indicators, goals and targets, and restrictions. Herein, the following stakeholders are considered:

i) research institutions,
ii) government,
iii) certification bodies,
iv) sustainability managers.

2.2.3 Benefits of a digital product passport

The benefits of a DPP stretch across the entire value chain, and various potential benefits are recognized in the literature, see Table 3. A DPP accelerates the transition to a circular economy by facilitating various circular practices (Götz et al., 2022). By providing enhanced traceability of a product, a DPP enables stakeholders to make better informed decisions and encourages circular practices (Adisorn et al., 2021; Götz et al., 2022; Heinrich & Lang, 2019; Walden et al., 2021; Watson et al., 2023). The tool enables resource optimization (Götz et al., 2022) and assessment of future material and product flows (Heinrich & Lang, 2019). Consequently, there is a general improvement of product flows, for instance, the value of products is retained or increased, the amount of waste is reduced and recycling rates are improved (Götz et al., 2022; Heinrich & Lang, 2019; Walden et al., 2021). It is also recognized that a DPP could create space for new innovations in circular design and new business models (Götz et al., 2022; Heinrich & Lang, 2019; Walden et al., 2021). Another key aspect of a DPP is its provision of a centralized source of data, in a comparable and a standardized format (Walden et al., 2021). Stakeholders are enabled easy access to reliable information, and the storing, processing and utilizing of data is facilitated (Götz et al., 2022). Moreover, processes regarding e.g. compliance checking, certifications (Plociennik et al., 2022b) and diligence due efforts are facilitated (Walden et al., 2021).

Table 3. Benefits of a DPP.

Circularity	Accelerates transition to circular economy (Adisorn et al., 2021; Ducuing & Reich, 2023; Götz et al., 2022; Heinrich & Lang, 2019; Jansen et al., 2023; Navarro et al., 2022; Plociennik et al., 2022b; Walden et al., 2021)
	Fosters traceability and transparency (Adisorn et al., 2021; Götz et al., 2022; Jansen et al., 2023; Plociennik et al., 2022b)
	Promotes sustainable and circular design, sourcing, manufacturing and business models (Götz et al., 2022; Heinrich & Lang, 2019; Walden et al., 2021; Watson et al., 2023)
	Keeps or increases the value of materials, products and components (Heinrich & Lang, 2019; Walden et al., 2021), reduces waste and use of virgin resources (Heinrich & Lang, 2019), increases rate of recycling (Walden et al., 2021)
	Supports a low-carbon transition (Adisorn et al., 2021) and industry climate neutrality (Götz et al., 2022)
	Enables the idea of buildings as material banks (Götz et al., 2022)
Resource efficiency	Supports resource optimization and energy efficiency strategies (Götz et al., 2022)
	Assessment of future material flows (Heinrich & Lang, 2019)
	Reduces costs through managing resources (Heinrich & Lang, 2019)
	Improves decision-making (Adisorn et al., 2021; Götz et al., 2022; Heinrich & Lang, 2019; Walden et al., 2021; Watson et al., 2023)
	Improves collaboration (Plociennik et al., 2022b)
	Improves logistics as well as reversed logistics (Götz et al., 2022; Heinrich & Lang, 2019)
	Improves enforcement tools and facilitates market surveillance mechanisms (Ducuing & Reich, 2023; Walden et al., 2021)
	Facilitates compliance checking and certification processes (Plociennik et al., 2022b)
	Enables diligence due efforts e.g. regulatory requirements (Walden et al., 2021)
	Monitoring of socio-economic and environmental impacts (Durand et al., 2022)
	Prevents greenwashing, supports organizations to monitor sustainability indicators and claims (Adisorn et al., 2021; Götz et al., 2022)
	Provides competitive advantage (Jansen et al., 2022)
	Opens new markets for producers and manufacturers (Götz et al., 2022)
	Management of supply and demand (Heinrich & Lang, 2019)

Data management and utilization	Access to reliable data in a standardized format (Götz et al., 2022; Plociennik et al., 2022b; Walden et al., 2021)
	Easier retrieval of information (Ducuing & Reich, 2023; Heinrich & Lang, 2019; Koppelaar et al., 2023)
	Enables storing, processing and utilizing data for complex value chains (Götz et al., 2022)
	Removes informational barriers (Adisorn et al., 2021; Ducuing & Reich, 2023; Navarro et al., 2022; Walden et al., 2021)
	Facilitates innovative data utilization (Watson et al., 2023)

2.2.4 Challenges in the implementation of a digital product passport

Generally, the functionality of the DPP is determined by four identified requirements: (i) access control, (ii) inclusivity, (iii) flexibility, and (iv) data quality (Guth-Orlowski, 2021). This section presents the challenges and barriers that pertain to each requirement. A summary of the identified challenges and barriers can be seen in Table 4.

Firstly, the DPP necessitates **access control**. The mechanisms related to access control of the system need to ensure that organizations' intellectual property rights and manufacturers' trade secrets are not put at risk (Guth-Orlowski, 2021). Protecting intellectual property and confidentiality regarding business information is considered a significant challenge (Ducuing & Reich, 2023; Durand et al., 2022; Götz et al., 2022; Koppelaar et al., 2023; Navarro et al., 2022; Plociennik et al., 2022b; Walden et al., 2021). Such information is, for instance, the composition of a product or its supply chain (Guth-Orlowski, 2021). Another example is the product performance data that is generated in the use-phase, e.g. consumer data, that could be important for fostering circular practices, however, consumers may be concerned about the use of their data (Ducuing & Reich, 2023). Furthermore, GDPR issues may rise regarding consumer data, such as data on energy consumption, product use and information on product location (Ducuing & Reich, 2023; Götz et al., 2022). Data governance challenges are considered as a major challenge, where its absence raises questions about storing, processing and using data (Ducuing & Reich, 2023).

Secondly, **inclusivity** is required of a DPP, in order to maximize the potential and benefits for each actor (Guth-Orlowski, 2021). Moreover, it needs to be accessible and in a user-friendly format (Walden et al., 2021). Herein, factors that may pose as a challenge involve are, for instance, associated costs (Cura et al., 2022; Saari et al., 2022), technical hurdles (Saari et al., 2022), cultural aspects (Cura et al., 2022), geographical barriers (Cura et al., 2022) as well as differences in environmental, legal, and social regulations (Cura et al., 2022). Additionally, considering SMEs, the DPP should not add burden in terms of human resources, related costs, available infrastructure, data analytics and time (Cura et al., 2022). Moreover, technical hurdles should not either pose as a barrier (Saari et al., 2022).

Thirdly, the DPP needs to be **flexible** and constantly evolving, as global supply and value chains can be complex with a large number of actors involved (Guth-Orlowski, 2021). In order to be user-friendly, it needs to be easy to add new organizations, actors or stakeholders to the DPP, and also to remove information and actors that are no longer required (Guth-Orlowski, 2021). Flexibility poses as a challenge especially in the construction industry, where buildings and infrastructure can have multiple owners and occupation profiles (Luscuere, 2017). Furthermore, the continuous feeding of data can be especially challenging in the use-phase (Adisorn et al., 2021).

The data fed into a DPP needs to be of high **quality**, i.e. correct, reliable and verifiable (Guth-Orlowski, 2021). In other words, "garbage in – garbage out" should be avoided (Saari et al., 2022), otherwise, the DPP cannot be effective. Regarding the quality of overall contents in a DPP, it should follow the data minimization principle (Saari et al., 2022). The DPP should only contain necessary data, and as little as possible (Saari et al., 2022). End-users might have concerns regarding data quality in terms of its accuracy, its fitness for future use and whether it is up to date (Ducuing & Reich, 2023). Construction products can be long-lived, thus, it should be ensured that the data inputs are still valid decades later.

Overall, a significant challenge that spans over all aforementioned categories is the lack of standardization and framework. For instance, there is no unified approach on what data a DPP should include, which also includes the absence of standardizations of metrics and measurements, such as carbon footprint declarations (Walden et al., 2021). Moreover, data collection and storage methods (Cura et al., 2022) as well as the format for different product types (Walden et al., 2021) also lack standardization.

Table 4. Challenges and barriers in implementation of a DPP.

Challenges in the implementation of a DPP
Lack of a data governance model (Ducuing & Reich, 2023)
Data privacy concerns (Cura et al., 2022; Ducuing & Reich, 2023)
Protecting intellectual property and confidentiality (Walden et al., 2021)
Data quality (Ducuing & Reich, 2023; Saari et al., 2022)
Differences in environmental, legal and social regulations (Cura et al., 2022)
Cultural aspects (Cura et al., 2022)
Geographical barriers (Cura et al., 2022)
Standardization of data content and format (Cura et al., 2022; Walden et al., 2021)
Standardization of format for different product types (Walden et al., 2021)
Standardization of metrics and measurements (Walden et al., 2021)
Standardization of infrastructures (Cura et al., 2022)
Associated costs (Cura et al., 2022; Saari et al., 2022),
Technical barriers (Saari et al., 2022)
Required human resources, investment, time (Cura et al., 2022)

2.2.5 Data requirements for a digital product passport

Jensen et al. (2023) distinguishes in their review four types of data points for a DPP, categorized based on availability and importance: *out of scope data*, *supportive data*, *focused development data* and *critical data*. *Out of scope data* has low availability and low importance, therefore, not regarded relevant for a DPP. *Supportive data* has high availability and low importance, and could be incorporated in a DPP as it is readily available, however, is not considered essential, at least in the early stages of implementing and designing a DPP. *Focused development data* has low availability and high importance, thus, valuable particularly for decision-making, although requires extensive work by stakeholders to generate and structure this type of data. Lastly, the critical content of a DPP that contributes to its value to decision-making for circularity is retrieved from *critical data* with high availability and high importance. Jensen et al. (2023) identified 28 data points, which were further grouped in seven data clusters. These data clusters were further simplified and concretized into four data types: (i) manufacturing data, (ii) usage data, (iii) end-of-life data, and (iv) lifecycle data, see Figure 3 (Jansen et al., 2023; Plociennik et al., 2022b).

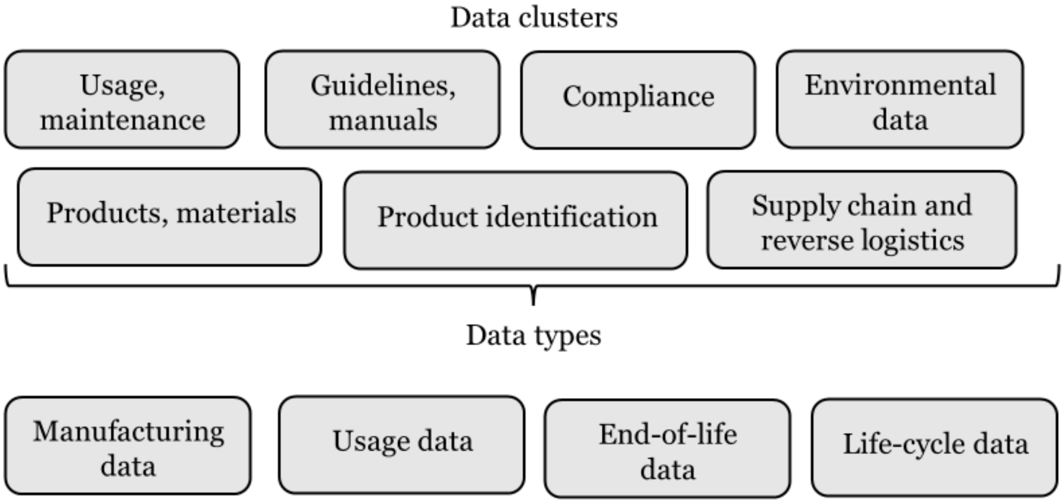

Figure 3. Identified data requirements in the literature (Jansen et al., 2023; Jensen et al., 2023; Plociennik et al., 2022b).

Manufacturing data includes, for instance, documentation on the manufacturing process, information on the composition of the products, its materials and weights used in each component, physical and chemical properties, and information regarding hazardousness of materials. Usage data involves documentation on all changes made to the product, e.g. any parts that have been replaced or repaired, or any damages done to the product. End-of-life data involves reporting and documentation of the collection, sorting and treatment practices, such as the applied waste management method. Finally, life-cycle data can involve information on guidelines for storage and usage, information on environmental impacts and social life cycle assessment. Examples of more specific data requirements for each can be seen in Table 5. (Jensen et al., 2023)

The aforementioned data type requirements function as a general guideline, as the requirements depend on several criteria, such as the complexity of the product, intricacy of the life cycle, value of the product as well as harm potential (Plociennik et al., 2022b). Moreover, the requirements are not tailored to a specific industry. As the value chain is complex with many layers and the data requirements vary between actors, a more detailed analysis of the needs of each actor is required to determine the contents of a DPP (Durand et al., 2022).

Table 5. Examples of each data type (adapted from Plociennik et al., 2022b; Jensen et al., 2023).

Data type	Examples
Manufacturing data	Manufacturing process, documentation Composition of product Material composition Physical and chemical properties Hazardous substances Product identification (e.g. serial number) Manufacturing date Country of origin Product-specific regulation (RoHS/REACH)
Usage data	Changes made to the product Recorded damages Location External environment Manuals for e.g. product, service Guidelines for e.g. installation, disassembly Safety instructions
End-of-life data	Reporting on collection, sorting and treatment Waste sorting guidelines Recycling partners
Life cycle data	Number of life cycles Labour conditions Environmental footprint Social lifecycle assessment

Some EU-regulations more directly or indirectly stipulate the content of a DPP. The DPP could centralize information on, for instance, chemical substances regulated under REACH (European Commission, 2006) and substances of concern under the Waste Framework Directive (European Commission, 2018). The Construction Products Regulation (CPR) (European Commission, 2022b) will influence the required contents of a DPP for construction products, e.g. regarding assessment and certification, declarations of performance (DoP) and environmental product declarations (EPD).

3 Methodology

In order to answer the research questions formulated in this thesis, two methods were used for the data collection process. The study conducted in this thesis is both qualitative and quantitative study, with both exploratory and explanatory qualities. Stakeholder interviews were conducted as a qualitative study, whereas a survey was conducted as a quantitative study. This section describes the methods used for data collection and data analysis. Also, this section aims to justify the choices of methodology. Finally, methodological limitations are discussed. The overall research process can be seen in Figure 4.

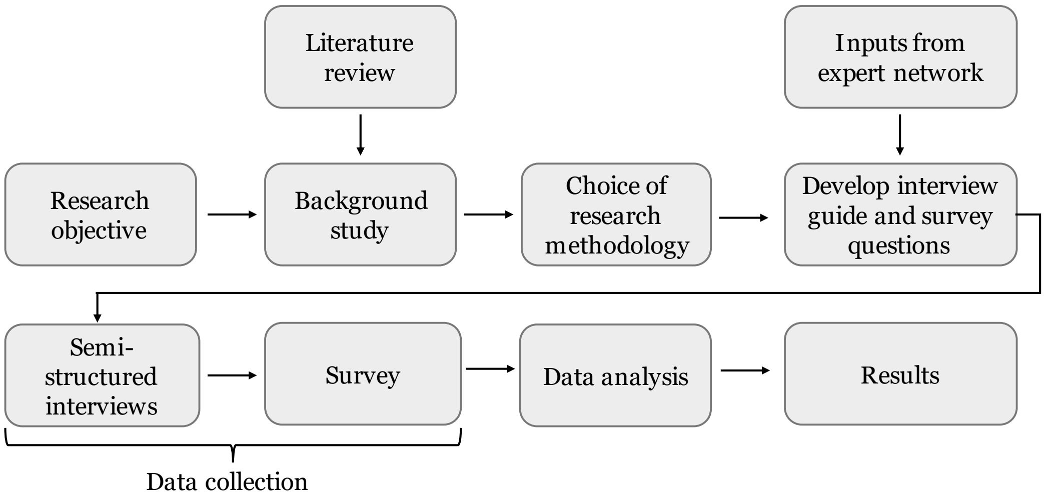

Figure 4. The overall research process.

3.1 Data collection

This subsection presents the data collection in the research process. Both stakeholder interviews and a survey were conducted. These methods are described, and the research sample is introduced.

3.1.1 Stakeholder interviews

In stakeholder interviews, the aim was to obtain insights on DPPs from the perspective of key stakeholders in the construction industry. The interviews aimed not only to recognize the benefits and barriers of a DPP, but also to assess the attitudes and current views. A qualitative approach was chosen as it provides a more holistic understanding of a phenomenon that is yet at its infancy.

A semi-structured interview was chosen as a qualitative research method. In this method, the interviewer follows a structured interview guide, while there is also room for versatility, flexibility and follow-up questions (Saunders et al., 2007). This method also allows the collected data to be comparable (Saunders et al., 2007). Semi-structured interviews are frequently conducted as an exploratory and explanatory research method (Saunders et al., 2007), and is the most frequently used method in qualitative research (DiCicco-Bloom & Crabtree, 2006). Thus, regarding the research objectives, a semi-structured interview was deemed as a suitable method for data collection.

The interview guide 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) circular economy, (ii) data and traceability for circularity purposes, (iii) benefits of a DPP, (iv) data requirements of a DPP, and (v) barriers and challenges in implementing a DPP. Overall, the interview guide consists of 21 main questions with sub-questions, see Appendix I. The questions were designed to be open-ended, encouraging in-depth responses by participants and avoiding questions that elicit yes or no answers. Moreover, the questions were carefully worded to ensure clarity and conciseness. Finally, the interview outline was further validated with a test interview.

The interview participants were carefully considered, as the data quality directly affects the integrity of the data for the study, as highlighted by Saunders et al. (2007). Thus, the interviewees were selected through a purposeful sampling strategy with emphasis on the variation of participants, as according to the principles presented in a study by Palinkas et al. (2015). This strategy is widely used in qualitative research in selecting information-rich participants related to the phenomenon of interest (Palinkas et al., 2015). Therefore, the aim was to assign each interviewee to a part of the value chain that their organization represents, to ensure a versatile constitution of the research sample. Based on the defined end-users of a DPP (see Section 2.2.2.) in the context of the construction industry, the data requirements of a DPP (see Section 2.2.5.) and the life-cycle stages (see Section 2.1.3.), five key stakeholder groups were defined:

i) design and manufacturing,
ii) construction,
iii) end-of-life management,
iv) research and development (R&D), and strategy,
v) government and policy bodies.

The interview participants were contacted from the extended network of the ICEBERG-project (an EU-funded research project focused on circular economy-based solutions demonstrating the efficient recovery of resources from end-of-life construction materials) and provided with a background document on the topic, to ascertain their sufficient knowledge on the subject. A total of ten interviews were conducted, of which nine were one-on-one interviews, and in one interview, two interviewees participated simultaneously. All interviewees except from one represented an organization based in Finland, whereas one interviewee represented an organization from Belgium. One of the interviews conducted was a test interview for expert validation of the interview guide, but after careful consideration, the test interview was included in the final analysis due to its valuable insights. Details of each interview can be seen in Table 6. The interview guide was sent to all participants a few days prior to each interview, allowing them to familiarize with the subjects. All interviews were held via Microsoft Teams, recorded, and automatically transcribed[1]. The interviews were held in Finnish or English.

Table 6. Details of the interviews.

Key stakeholder group	**Interviewee title**	**Interview date**	**Interview length**
Design and manufacturing	Sustainability Manager, Director of Development	27.4.2023	66 min
Design and manufacturing	Specialist	3.5.2023	109 min
Design and manufacturing	Construction product approval specialist	10.5.2023	75 min
Construction	Technical Director	25.4.2023	71 min
End-of-life management	Director of Business Development and Marketing	18.4.2023	65 min
R&D and strategy	Research Scientist	14.4.2023	34 min
R&D and strategy	Project Manager	24.4.2023	57 min
R&D and strategy	Director in a joint interest organization	11.5.2023	60 min
Government and policy bodies	Policy Advisor	24.4.2023	62 min
Government and policy bodies	Senior Ministerial Advisor	17.5.2023	40 min

[1] Prior to each interview, consent for recording and using the interview results in the thesis was asked.

3.1.2 Survey

In the survey, the aim was to gather quantitative data on the research topic, and to complement and verify results of the interviews. Moreover, this kind of deductive research approach allows for the collection of standardised quantitative data from a larger sample size, as well as easy comparison of responses (Saunders et al., 2007). Furthermore, this method is widely used for data collection, as it is an efficient way to gather responses from a large sample prior to quantitative analysis (Saunders et al., 2007). Regarding the research objectives, a survey was deemed as a suitable method.

The survey outline was based on the research questions, background study, and interview guide, revolving around three themes. Each theme focused on each research question of the thesis: (i) benefits of a DPP, (ii) data content requirements of a DPP, and (iii) barriers in implementing a DPP. In total, 28 questions were formulated, see Appendix II. The questions were close-ended, requiring an answer, with the addition of optional open-ended questions allowing the respondent to elaborate on their answers. Moreover, the questions were carefully worded to ensure clarity and conciseness. The survey was made with Microsoft Forms. Finally, the outline was further refined and validated based on expert opinions from colleagues within the ICEBERG-project.

The survey was intended to be answered by experts in the construction industry, and was sent to the extended network of colleagues within the ICEBERG-project. In total, 47 responses were collected. The respondents were, in the same manner to the interviews, divided into key stakeholder groups (see Section 3.1.1.), see Figure 5. Job titles of the respondents are shown in Table 7. The respondents represented mainly large enterprises (32 respondents), and also medium-sized enterprises (6 respondents), small enterprises (6 respondents) and micro-sized enterprises (3 respondents). Organizations from different countries in Europe were represented, see Figure 6.

Table 7. Job titles of survey respondents.

Architect	Policy Advisor	Research Associate
Chief Executive Officer	Principal Scientist	Researcher (4)
Consultant (3)	Project Engineer	Sales and Business Development Manager
Director (4)	Project Leader (2)	Scientist
Director General	Project Manager (5)	Senior Researcher
Director of Research	R&D Director	Senior Scientist (2)
Engineer	R&D Engineer	Sustainability Junior Technician
Group Manager	R&D Manager	Technical Director
Leading Environmental Specialist	R&D Project Engineer	Unknown
PhD candidate (4)	R&D Project Manager	
	Research Assistant	

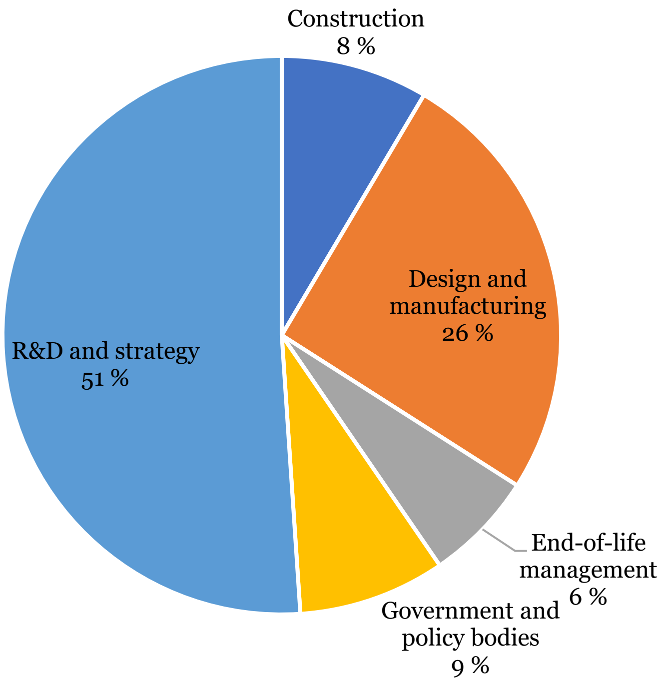

Figure 5. Distribution of stakeholder groups of the survey respondents.

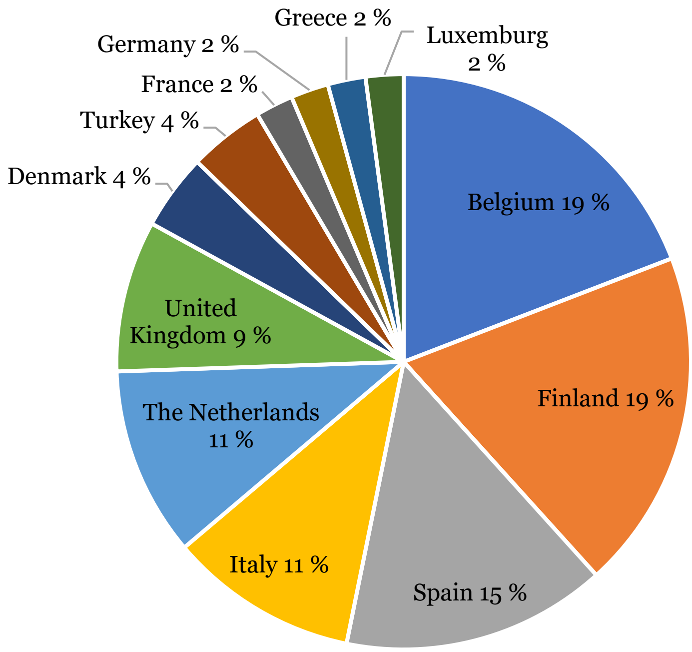

Figure 6. Distribution of survey respondents based on the country of organization.

3.2 Data analysis

Thematic analysis is a method to systemically identify, analyze and report themes, i.e. recurring patterns. Moreover, it has been suggested as a suitable method for analysing qualitative datasets, and is seen as a foundational method for qualitative analysis (Braun & Clarke, 2006). One prominent feature is the flexibility of the method, as it can be applied to several types of data sets, sample sizes and sample constitutions, as well as methodological approaches (Braun & Clarke, 2017). As there is no standardized approach to analysing qualitative data (Saunders et al., 2007), and based on the research objectives, thematic analysis was considered as a suitable method for analysing the collected data from stakeholder interviews.

A six-step framework for thematic analysis developed by Braun & Clarke (2006) was applied in this thesis, as it is the most widely accepted framework for this purpose (Kiger & Varpio, 2020). The framework follows six steps: (i) familiarizing with data, (ii) generating initial codes, (iii) searching for themes, (iv) reviewing the themes, (v) defining and naming themes, (vi) producing the report.

In step one, familiarizing with data occurred through re-watching recorded videos of interviews, in order to ensure that nothing relevant was missed from the interviewer during the interview. Moreover, notes during interviews and automated transcriptions by Microsoft Teams were reviewed and corrected. Transcriptions in Finnish were translated into English. In the following step, initial codes were generated. In this context, codes are building blocks for themes. Herein, data relevant to the research objectives were identified and labelled, with the aim to group codes into themes. The third step involved identifying themes based on codes. Here, the codes were assigned and categorized to a theme. Three themes were identified: benefits of a DPP, barriers in implementing a DPP, and data content needs of a DPP. Each theme revolves around each research question of the thesis. The pre-determined themes of the interview guide facilitated this step. In both step two and three, a qualitative data analysis software, NVivo, was used to code the interview data. In step four, themes and codes were reviewed, in order to ensure relevance of each code and allow for modifications. In step five, final themes are clearly assessed, defined and stated. Finally, the last step, involves producing a report based on the results from the thematic analysis.

3.3 Methodological limitations

The research methods applied in this thesis has some limitations. Due to the time constraint, there was a limited number of interviews. Time and resource constraints also limited the depth of information as well as the scope of questions, in both interviews and survey. Considering the sample constitution, some key stakeholder groups (construction and end-of-life management) were represented only by one interviewee. Additionally, there was an uneven distribution of stakeholder groups among the survey respondents. The geographic focus of interviews was on Finland, as nine out of ten interviewees represented organizations based in Finland. Also, when interviewing participants representing an organization in Finland, the interview guide was translated into Finnish and the interviews were held in Finnish, after which the transcriptions for data collection were translated to English. Thus, the translation from English to Finnish, and vice versa, might have affected the wording and nuances in the questions, leading to different interpretations by both interviewees and the researcher. Moreover, the wording of survey questions might have led to different interpretations. Other limitations of the research methods involve biases such as response bias, confirmation bias and observer bias.

4 Results and discussion

This chapter presents, interprets, and discusses the results from the interviews and survey. It consists of three subchapters, each surrounded around each research question of the thesis: (i) benefits of a DPP, (ii) data requirements for a DPP, and (iii) barriers in implementing a DPP. In each subchapter, both interview and survey results are presented, then, critically reviewed and discussed.

4.1 Benefits of a digital product passport

This section aims to answer the first research question "What are the benefits of a digital product passport for key stakeholders?", by analysing the potential and benefits of a DPP that have been recognized in this study. First, the results and analysis are presented. Then, in the final subsection, the results of this section are discussed.

4.1.1 Traceability

Among interviewees, there was a strong consensus that a DPP improves traceability. This is supported by the survey results, where all respondents agreed that traceability and transparency would be enhanced. Also, two survey respondents represent an organization that already utilizes a DPP, and both respondents strongly agreed with this statement.

The results from interviews show that the primary benefits of a DPP stem directly from the information it provides. The access to product information, history and life cycle was considered beneficial. Moreover, the digitalization of product information and enabling direct access to information for all actors throughout the value chain was seen as a valuable aspect.

It was observed that the advantage of traceability takes various forms along the value chain. Regarding actor-specific benefits of traceability, for instance, tracing products allow designers to quickly access information, contractors to manage the duration of construction, or government agencies to improve policy processes. Additionally, tracing products and their history could facilitate practices in demolition and dismantling, through facilitating the management of dismantled products. It was emphasized that due to the long lifespan and complexity of a building, it is currently difficult to assess potential damages sustained by products, consequently hindering circular practices for these products. Moreover, the digital representation of material proportions within a structure, for instance, whether any materials are already recycled, would further facilitate the assessment of different products.

Finally, managing product information emerged as a relevant aspect in interviews, where participants recognized the need for better management of product information. However, traceability systems are not utilized by organizations and there is no single coherent system involving all actors for this purpose. Furthermore, data and information are rather scattered, hindering effective traceability.

4.1.2 Circular practices

All stakeholders agreed that a DPP will foster circularity. A majority of the interviewees considered that the DPP would especially foster circular practices that extend the lifespan of product and its parts, more specifically R3-R7 (reuse, repair, refurbish, remanufacture, repurpose). One interviewee stated that these practices are supported by, for example, appropriately selecting products for specific purposes and through effectively managing the life cycle of a building. Additionally, the ability to trace products enables efficient reusing of dismantled products. Circular practices related to a useful application of materials, i.e. R8-R9 (recycle, recover), were also believed to be fostered with a DPP. Least emphasis was placed on practices related to smarter product use and manufacture, R0-R2 (refuse, rethink, reduce). Quantified results obtained from interviews can be observed in Figure 7.

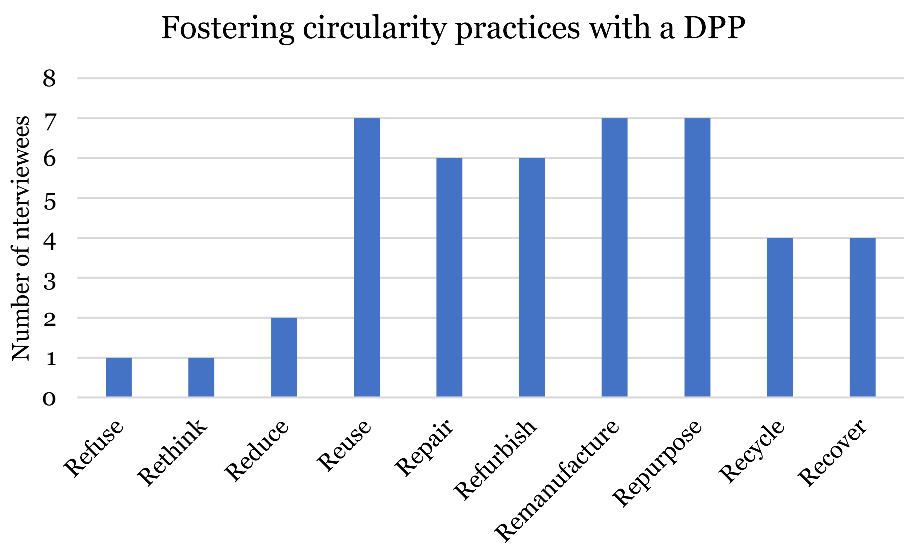

Figure 7. Results from 9 interviews on circular practices fostered by a DPP.

In one interview, the facilitation of the reuse practice (R3) with a DPP was strongly highlighted. In their organization, it had been noticed that despite the high reuse potential of products, they are not reused due to quality uncertainties. Consequently, customers become hesitant to invest in these products, restricting the reuse-practice. A DPP that traces a product's history would allow potential customers to make more informed assessments of the condition and quality. The interviewee highlighted that this procedure is currently difficult, costly and time-extensive, especially in the construction industry, where products have a rather low integral value compared to virgin resources. Thus, investment is currently not profitable. Through using a DPP, the reuse-practice could be facilitated greatly.

4.1.3 Accessibility and user adoption

The majority of interviewees considered the direct and easy access to information as a pivotal benefit. A few stakeholders emphasized that systematic data sharing and clear presentation of contents would further improve accessibility. This entails incorporating all essential, relevant information for the user and downstream user, and that it is digitally documented and preserved until the end of the products life cycle. Additionally, all kinds of documenting, saving and utilizing information would be facilitated with a DPP. Currently, these processes are considered quite manual, with fragmented information in different databases and platforms.

In some interviews, the topic of accessibility was further discussed, whether the interviewees would adopt a DPP and which actors would be the primary beneficiaries. Two interviewees predicted that a DPP would eventually become useful for all actors. From a designer's point of view, the DPP was considered highly practical and useful. In contrast, a representative from a construction organization believed that users during maintenance are the primary beneficiaries. An interviewee involved in end-of-life management expressed that this topic had been addressed at the organizational level, suggesting that demolition workers might not experience direct benefits of a DPP, since it does not directly impact the demolition process. This interviewee further elaborated that designers are the primary beneficiaries of a DPP. Participants involved in R&D and strategy did not consider the DPP very useful in their work. Some interviewees expressed the belief that the benefits of a DPP are mostly related to the owning and managing organizations. In the survey, respondents were asked to estimate how often they would use a DPP. The results were scattered and no pattern was identified.

4.1.4 Resource efficiency

All interviewees agreed that a DPP would save resources. This was recognized in one or more of the following aspects: time, costs, and workload. Each aspect would contribute to improved resource efficiency to some extent.

Time savings was the most brought up aspect by interviewees. They expressed that a DPP would save time in various processes throughout the value chain. Three key areas were identified during the interviews, regarding how a DPP saves time.

Firstly, it was observed that a DPP would save time in information retrieval due to the readily available information, eliminating issues of scattered or missing information. This could create new opportunities in organizing and planning the construction phase, for instance, by optimizing the transportation and positioning of products. Consequently, stakeholders could manage the duration of the construction phase. In terms of end-of-life practices, it was believed by interviewees that a DPP could facilitate the assessment concerning products worth to dismantle, thus, saving time and also facilitating sales measures of dismantled products. The findings from interviews are supported by the survey results, where 85 % of the respondents agreed that a DPP would facilitate planning and procurement. Moreover, 59 % agreed that a DPP would save time during construction and demolition.

Secondly, findings show that a DPP would enhance the efficiency of processes regarding compiling, producing, distributing and implementing product information. Moreover, data collection would be more systematic and structured, which is a practice currently considered quite manual. In the survey, communication gaps with other stakeholders were identified as a pertinent issue. Furthermore, it can be observed that SMEs experience more often information and communication gaps compared to larger organizations.

Thirdly, it was found that a DPP saves time by providing data that can be used for different purposes. The data would not be needed to be replicated or sourced again. For instance, one interviewee suggested that this could create opportunities for integration with other tools, such as those used to evaluate the environmental impact of buildings.

Regarding **costs**, it was believed by the majority of interviewees that a DPP would yield cost savings, as a result of various factors, such as savings in time and workload, facilitated decision-making, and the streamlined information flow. Moreover, interviewees highlighted that a DPP would add competitive advantage for organizations, for instance, by its impact on the reliability of the company perceived by the consumer, or by including a DPP as an asset. These findings are in alignment with the survey results, where 68 % of the respondents agreed that a DPP would contribute with financial benefits and competitive advantage.

One interviewee provided an example of, such as when a product's life cycle is shorter than expected, a DPP would allow the end-user to find a suitable replacing product or information on repairs. The user would be able to manage the costs associated with repair and replacement, and perhaps anticipate the problems and follow-up. Consequently, this would yield financial benefit to the property owner.

A seller can provide a more reliable option, with the DPP demonstrating the quality, suitability and eligibility for intended use. Thus, the DPP could add value to the sales stages, e.g. when selling a building or dismantled products. Another sales argument for the customer is that having accurate and relevant data further facilitates future maintenance, use and repair. This is especially relevant for dismantled products, as understanding their history becomes more crucial when it comes to reusing.

Manufacturers can capitalize on including their data in a DPP. For example, in the event of product damage, the end-user may contact the manufacturer. This creates an opportunity for the manufacturer to sell the same product again.

In terms of **workload**, some interviewees expressed that a DPP would alleviate the workload, especially for designers and product procurement. This is mainly due to the provision of a centralized source of information. One key aspect of reducing workload, as emphasized by the interviewees, is that a DPP would facilitate various decision-making processes at many stages. By providing comprehensive information, the DPP enables end-users to make informed decisions regarding product choices. For instance, end-users can easily compare environmental impacts and costs, assess the durability of products or identify suitable replacement products. One interviewee highlighted that reliable and transparent information would improve the quality of both the preparation and follow-up of policy processes. Another example involves the integration of digital product data into a building's climate report, potentially simplifying impact calculations. In the survey results, there was a strong consensus that a DPP would facilitate certification processes.

4.1.5 Construction product supply chains

In interviews, the participants were asked which construction product supply chain would benefit the most from a DPP. Here, the answers varied and there were no straightforward answers. Four interviewees did not consider a specific product group, stating that all physical products in a building would benefit from a DPP. Two participants believed that products with a short lifespan or products that often get changed, replaced or updated would benefit the most.

When further discussing about which construction product groups should be prioritized in the phased implementation of the DPP, some varying examples were provided. One interviewee suggested steel structures as a starting point, due to the ease in handling and reusing, as well as the significant environmental benefits. By providing more specific information on the thermal properties and previous procedures, end-users would be able to process the metal based on its actual quality, instead of according to the lowest quality standard. Another interviewee suggested concrete products, despite the complexity compared to other product groups. Conversely, another participant highlighted that due to the complexity of concrete, information management could become challenging as modifications may occur on site.

Based on the results of the survey, concrete, plastic and insulation products were considered to benefit the most from a DPP in terms of circularity. The results can be seen in Figure 8. Notably, the latter two product groups were not addressed during interviews.

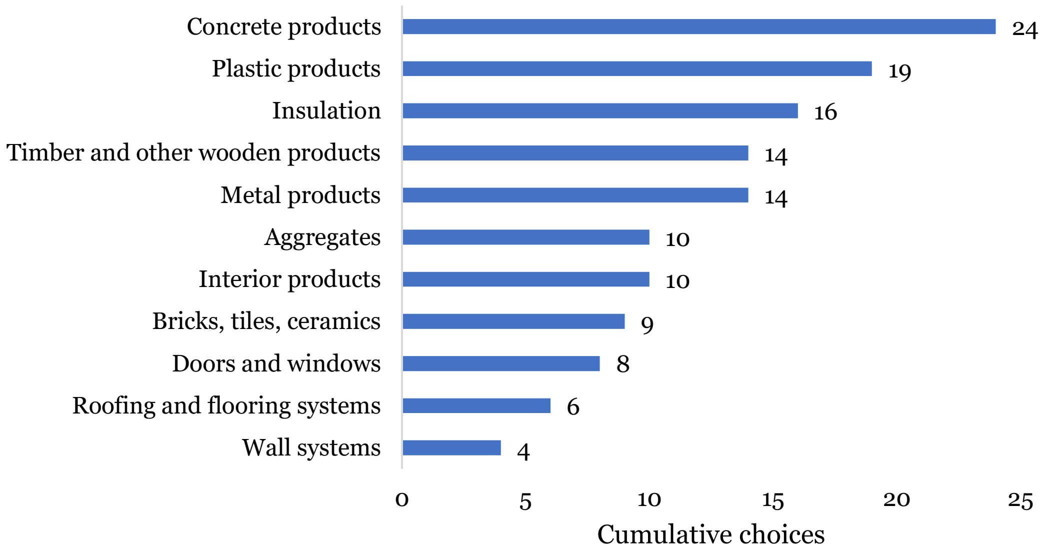

Figure 8. Survey results to the question "*Which of the following construction product supply chains would benefit the most of a DPP in terms of circularity purposes? Please select at most 3 options*".

4.1.6 Discussion

In light of the findings, it can be stated that the DPP providing traceability has multifaceted effects, connected to different stages of a product's life cycle. Naturally, since the function of a DPP is based on improving traceability, it is quite expected that this result is the most important and highlighted. Improved traceability with a DPP has been widely recognized in the literature (e.g. Adisorn et al., 2021; Plociennik et al., 2022a), although it often refers to a non-specific industry, with a fraction focusing on the construction industry (e.g. Götz et al., 2022; Heinrich & Lang, 2019). The information and communication gaps in the construction industry highlight the need for a traceability system, and the results suggest that the DPP has the ability to fill these gaps.

Further underscoring the value of traceability, the findings emphasize the role of the DPP in accelerating the transition to a circular economy. As stated by Adams et al. (2017), the research on circular practices in the construction industry are mainly focused on managing CDW with low circularity practices (R8-R9), with only a small part being reused. The study indicates that a DPP has the ability to shift to a higher circularity (R3-R7), with emphasis on the reuse-practice. Consequently, this could result in the reduction of waste, a higher use rate of secondary raw materials and the retention of product value. Despite the facilitated decision-making regarding reuse, the findings do not provide insights into the extent to which a DPP can improve consumer trust, especially when factoring in safety concerns related to a structure or a building. Furthermore, Luscuere (2017) highlights that the construction sector has numerous priorities, including cost-effectivity as well as health and safety. Consumers may still prefer purchasing new products over reusing, especially when it comes to products with low value. However, the potential for a DPP to improve reuse-practices could foster new business opportunities, such as take-back schemes for waste products or reverse logistics.

Regarding whether stakeholders would use a DPP, the study highlights areas for improvement and underscores the importance of involving all actors during the planning and implementing of a DPP. Designers and owning organizations are seen as primary beneficiaries, whereas stakeholders in R&D and strategy and end-of-life management do not see immediate benefits of a DPP in their work. This observation is further validated by the scattered survey results. To address this gap in stakeholder perceptions, there is a need to justify the benefits for all actors and to enhance the overall appeal of the DPP.

The study shows that a part of the improved resource efficiency is associated with better decision-making. By accessing reliable and comparable data, stakeholders can make informed choices and implement circular practices. Furthermore, as the findings indicate that the DPP could function as a connecting element in the value chain, it can be justified that this contributes to the facilitated decision-making. For instance, practices such as design for disassembly and adaptability could be facilitated, as designers can get additional insights on the end-of-life of products. Conversely, users on the end on the value chain are provided with instructions for disassembly and further use. It could also be justified, that, having insights on how products are managed and their wear and tear throughout its life cycle improves manufacturers' capabilities to optimize resource utilization and product development.

Additionally, manufacturers could be able to optimize the supply chain, thus, reduce production costs.

Findings indicate that the DPP could be useful during project planning and execution, not only by organizing the construction phase regarding e.g. logistics and transportation, but also by efficient resource allocation. Possibly, over time, the accumulated data could provide more insights on improving various processes and allow to track progress, for instance regarding procurement and inventory management. Through more efficient project coordination, facilitated assessment of a product's reusability and correct implementation of end-of-life practices, it could be argued that the DPP has the capacity to improve the CDW management. Demolition projects usually account for the largest share of CDW, thus, the DPP could contribute with significant improvements in the prevention and reduction of waste. However, as demolition projects face strict time constraints, it is important to ensure the DPP will facilitate these practices rather than add a burden. The interviewee representing end-of-life management expressed that the DPP may not directly impact the demolition process. Thus, careful considerations need to be drawn of these conclusions, whether the use of a DPP is practically feasible during demolition, and a gap is identified. Moreover, the resource savings are potentially larger for SMEs compared to larger organizations, as SMEs more frequently experience information and communication gaps, resulting in the growth of SMEs. However, the findings regarding improved resource efficiency offer only some insights. Also, there is no quantifiable data on how much resources a DPP could save.

The study also shows that improved data management will result in time and cost savings. This could support the view that long-term systematic data utilization with a DPP could introduce novel methods to process data, e.g. when integrated with other tools such as AI. Advancements in these areas could create space for new innovations in data management and analytics, for instance, developments of new models, tools and indicators. However, the study does not provide further insights into these aspects.

Regarding implementing the DPP in phases, the study could offer some practical implementations for future regulations. Adisorn et al. (2021) highlights prioritizing product groups that are suitable for the quickest possible implementation of the DPP. Conversely, the findings of this study suggest that the prioritizing of product groups can be approached in two ways. Firstly, if the aim is to maximize the environmental benefits, concrete products might be a suitable option. The challenges involve the complexity of concrete, e.g. regarding feeding data, which might discourage end-users in continuous use of the DPP. Secondly, if the aim is to start off successfully while laying the framework for other product groups, a simpler option could be more suitable, for instance, steel structures. Another option is short-lived product groups that quickly demonstrate the practical benefits of a DPP, encouraging end-users for further use. However, it needs to be highlighted that these findings require cautious interpretation, as the question could have introduced bias. Respondents from specific backgrounds might have been more inclined to favour their own research topic or industry. By offering three selections to choose from many options, the bias is potentially somehow reduced. Hence, these results can offer a starting point for future research, rather than definitive outcomes.

4.2 Data content needs of a digital product passport

This section aims to answer the second research question of the thesis: "What are the data requirements for a digital product passport for construction products?", discussing the needed data in order to realize the benefits mentioned in Section 4.1. First, the identified data requirements are presented. Then, the findings are discussed.

4.2.1 Identified data requirements

In both interviews and survey, all data types, i.e. manufacturing, usage, end-of-life and life-cycle data, were considered relevant in a DPP. Interviewees particularly emphasized manufacturing data, more specifically, the technical data, information on the product composition, physical and chemical properties, and other product information. Some interviewees pointed out that certain data may currently seem irrelevant, but turn out to be useful in the future or they may not recognize its relevance. Moreover, some interviewees highlighted that most of the information already exists, but is scattered. The relevance of each data type for each interviewee are presented in Table 8.

Table 8. Data type needs in order of relevance for each interviewee. Darker shades of green indicates that the data is considered crucial, green indicates important, whereas light green indicates that the data is still relevant, however, not equally important.

		Type of data			
Inter-viewee	**Stakeholder group**	Manufac-turing data	Usage data	End-of-life data	Life-cycle data
1	Design, manu-facturing				
2					
3					
4	Construction				
5	End-of-life management				
6	R&D and strategy				
7					
8					
9	Government and policy bodies				
10					

In the survey, stakeholders were asked to rank the provided data examples according to relevance. A color-coded scheme regarding the level of relevance of each data type for stakeholder groups can be seen in Table 9. In comparison to interviews, the survey results placed a greater emphasis on end-of-life and life-cycle data.

Out of *manufacturing data*, the information of material contents (such as physical and chemical properties, hazardous materials and the source of materials) was considered the most important by survey respondents. Stakeholders in end-of-life management placed most emphasis on manufacturing data, whereas those involved in R&D and strategy did not regard it as highly. *Usage data* was considered equally relevant among stakeholder groups. Moreover, the survey results indicate that usage data was considered the least important among all data types. All key stakeholder groups placed most emphasis on *end-of-life data* out of all data types. More specifically, recycling and disposal instructions including extended producer responsibility (EPR) obligations emerged as the most pivotal compared to other data examples in all data types. Government and policy bodies considered end-of-life data the most crucial. Finally, *life-cycle data* was also deemed crucial by survey respondents, particularly the information on environmental impacts and circularity performance.

Overall, patterns of survey results indicate that stakeholders involved in construction as well as design and manufacturing ranked data types similarly. Stakeholders in end-of-life management generally ranked all data types the highest. Respondents from government and policy bodies placed greatest emphasis on end-of-life data. Finally, those involved in R&D and strategy generally ranked the data types lower than other stakeholder groups.

Table 9. Survey results of data relevance for stakeholders. The relevance levels are illustrated using a colour scale: shades of yellow indicate lower relevance, while increasing shades of green indicate higher relevance (Constr. = Construction, D&M = Design and manufacturing, EoL = End-of-life, Gov. = Government and policy bodies, R&D = R&D and strategy).

		Constr.	D&M	EoL	Gov.	R&D
Manufacturing data	Material contents					
	Technical data					
	Product identification					
	Quality control measures					
Usage data	Changes made to the product					
	Recorded damages					
	Energy consumption					
	User & safety manuals					
End-of-life data	Instructions on removal of hazardous materials/product dismantling					
	Recycling/disposal instructions					
	Reporting of collection, sorting, pre-treatment					
Life-cycle data	Environmental impacts					
	Social impact					
	Circularity performance					
	Sustainability certifications					

4.2.2 Discussion

The study suggests that the main data types to be included in a DPP are manufacturing, usage, end-of-life and life-cycle data, as in agreement with the study of Plociennik et al. (2022b). These findings regarding the four main data types are not new, however, in the context of the construction industry it does contribute to the broader scope in the field. In interviews, it was observed that the required data was discussed at a general level, focusing on the four data types, rather than exploring specific data elements. Moreover, interviewees did not propose or recognize other data requirements outside the examples presented. Herein, one possible limitation of the interview findings is that the data types were provided to participants, possibly limiting their responses. Nevertheless, the survey functioned as a complementary research method, allowing to collect responses on more specific data elements. The study shows that these four data types can serve as a general guideline, and the proposed next steps involve determining product group specific data requirements. Possibly, the expected lifespan of products may determine the level of detail and specific content. Another consideration is the potential need to further add key stakeholder groups for different construction product groups, as they may differ from value chain to another.

Findings show that stakeholders prioritize data differently, however, the disparity is relatively minor. Luscuere (2017) discusses that every stakeholder does not require the same information. However, it is important to ensure that all information is available to all stakeholders, otherwise it may contradict the idea of the DPP being transparent to all stakeholders.

The results show that the most emphasis was placed on manufacturing, end-of-life data and life-cycle data, of which the latter two could indicate a mindset shift towards circularity or a need for improving environmental impact assessment. The least emphasis was placed on usage data, which could contradict the significance of the DPP facilitating the reuse-practice (as discussed in Section 4.1.6). This could indicate that as information on, for instance, sustained damages, is currently not required from stakeholders, it is not considered relevant to include in the DPP and seen as a means to add burden for data input. Moreover, Adisorn et al. (2021) discusses that generating data from the use-phase is particularly challenging, which is an aspect this thesis does not take into consideration concerning stakeholders associated with the use-phase. Some interviewees did question the need for additional data than what is currently required. This could indicate that the DPP is primarily seen as a tool for centralizing information rather than a novel, innovative tool for transforming into a circular economy. It could also indicate that the willingness of data sharing is limited to what regulations require. Future regulations will strongly influence the contents of a DPP, particularly the revised CPR. The results suggest that if additional requirements are imposed, they should align with compliances or adhere closely to them. Another hypothesis is that usage data is irrelevant for short-lived products, especially those of low value, but becomes increasingly important for long-lived products. However, this thesis does not explore this aspect.

The results suggest that most of the relevant data is provided by manufacturers, thereby justifying their important role as an information source and actor, as also discussed by Adisorn et al. (2021). Therefore, it could be justified to further explore manufacturers' engagement in data sharing and utilization. The findings on the level of data needs of each stakeholder can provide insights on areas of improvement regarding the general appeal of a DPP, an important aspect in the successful employment of the tool. For instance, this observation could imply that R&D and strategy might need other sort of data in the DPP. For further research, there is a need to explore the data needs of each stakeholder group in more detail. Possibly, more key stakeholder groups could be added, for instance, designers and manufacturers could be distinguished. Key stakeholder groups could also be organized according to size, e.g. individual entrepreneurs, SMEs and larger organizations.

It is important to acknowledge that not all interviewees or survey respondents can be straightforwardly categorized into distinct stakeholder groups, due to potential overlaps and respondents with diverse backgrounds or job roles. Thus, the findings may not be directly transferable to each stakeholder group. Moreover, both sample size and constitution were limited. Key stakeholder groups of construction and end-of-life management were represented by only one interviewee. In both interviews and survey, stakeholders from R&D and strategy were the most represented, possibly overshadowing other significant groups such as construction. Thus, the findings may offer a limited viewpoint. The interview perspectives were centered on Finland, limiting the transferability of interview findings to the entire EU. More participants in these key stakeholder groups and from different EU-countries would have increased the generalizability of interview results.

4.3 Barriers and challenges in implementing a digital product passport

This section aims to answer the third research question of the thesis: "What are the barriers and challenges in implementing a digital product passport?". The identified barriers, challenges and conditions of a DPP are presented. Then, the results are critically discussed.

4.3.1 Identified barriers and challenges

Issues regarding **business confidentiality** was the most significant barrier recognized in interviews. These involve, for instance, protecting intellectual property and trade secrets, as well as reluctance in data sharing. In the survey results, there was a strong consensus among respondents regarding business confidentiality posing as a barrier.

In interviews, business confidentiality was considered as a barrier particularly for manufacturers, in the context of what data is required from them, at what level of detail, and what they are willing to share. This was also acknowledged by other actors than manufacturers. Furthermore, business confidentiality could become a greater challenge, if a DPP would require more information from certain actors compared to what is already required, such as in environmental product declarations or declarations of performance.

Requirements for a more detailed level of information may cause organizations to be unwilling to share data. This data includes, for instance, how a product is manufactured, certain additives, recipes and concentrations. Also, manufacturers might be reluctant to share their data, as it could be easy to, for instance, infer the production costs of a single production plant. One interviewee pointed out that a DPP might reveal material or product options that other actors or companies have yet to discover. Thus, this kind of point of view might hinder data providers to share a sufficient amount of information in a DPP. Incentives for sharing data could be benchmarking, improved marketing strategies and the validation of environmental claims about products, as provided examples by interviewees.

The aspect of **time** was not considered as a barrier in the interviews, at least not a significant one. One interviewee did acknowledge that adapting to a new digital technology could potentially require some time investment, but the recognized benefits would ultimately outweigh it. Another interviewee discussed the aspect of time in relation to the lifespan of buildings, expressing that managing information and keeping it up to date is a relevant challenge. Another interviewee emphasized that time is a critical factor during a demolition project, and that managing a DPP, e.g. data input, should not become a time constraint or add unnecessary delays. One interviewee believed that time could become a practical, concrete obstacle for SMEs involved in product categories with lower profit margins, compared to larger organizations involved in products with high turnover. So, if a similar regulation were imposed on product categories with a more marginal demand, it would likely be more of a concern. In the survey, there was a strong consensus that the lack of resources for data input and processing would pose as a challenge.

When discussing the **IT-expertise**, there was no consensus between interviewees whether it poses as a barrier or not. The interviewees who did not consider the lack of IT-expertise as a barrier, raised the IT-architecture, data architecture management and system continuity as a challenge instead. For instance, ensuring that the generated data flows seamlessly throughout the value chain and is effectively utilized was highlighted. However, if the DPP would require the adoption of an entirely new software, time would potentially become a greater barrier instead. In the survey, the majority of the respondents considered the lack of required IT-knowledge as a barrier.

Some interviewees emphasized that especially SMEs might encounter challenges regarding IT-expertise. They pointed out that larger suppliers, contractors, and clients typically have various programs and tools at their disposal, resulting in a significantly greater advantage, as opposed to lower levels in the value chain, e.g. individual builders, who might lack essential resources or knowledge. One interviewee believed that SMEs might have to outsource certain IT-tasks, resulting in increased costs and financial burdens, stating that their organization would not have the capacity to adopt a new software. In the survey, there was a strong consensus that financing aspects poses as a barrier, however, there was no clear pattern or consensus in the answers regarding the size of the organization.

In interviews, the **policy landscape** was discussed. Herein, there was no consensus between interviewees whether the DPP should be voluntary or mandatory. In contrast, the majority of survey respondents agreed that a DPP should be mandatory for all actors in order to reach the benefits.

Interviewees who believed the DPP should be voluntary, justified it from a market perspective. By spreading optimal market practices and the idea of managing digital product information through the market, the tool is able to evolve accordingly. Moreover, the development of a DPP would be more feasible. If a DPP is shown to be practical and functional, simultaneously widening the markets and contributing to sustainable construction practices, it will be adopted by all actors. One interviewee believed that a strong recommendation should be made instead, as the tool should be market-driven. The legislation should not interfere too much with the content of a DPP, as the content should be market-oriented and in compliance with EU-regulations. When regulating DPPs, it should specifically be a part of the EU-internal market system, in line with what the EU-regulations require in terms of product characteristics, manufacturer information, third-party verification and other necessary information and formats for submission.

Justifications for introducing mandatory DPPs varied. One interviewee highlighted that the DPP should become mandatory in order to advance in terms of circular economy. Another interviewee believed that if DPPs are made voluntary, the associated investments could be too large. Moreover, they expressed that a mandatory approach would facilitate regulation. Another interviewee in favour of mandatory DPPs expressed that it should leave enough development to the market.

4.3.2 Conditions of a digital product passport

In interviews, the benefits and data content needs of a DPP, as presented in Sections 4.1 and 4.2, were discussed in relation to conditions required for realizing the benefits. Three key areas were identified: conditions related to accessibility, standardization, as well as data quality and information management. A comprehensive overview of all conditions is presented in Table 10.

Firstly, the conditions related to accessibility, revolving around the ease, availability and practicality of a DPP, were frequently repeated in the interviews. In relation to accessibility, interviewees underscored the importance of involving all actors, also during the process of planning a DPP. Contribution of relevant data and participation of every actor is needed to ensure full traceability and transparency. An emphasis was placed on the inclusion of organizations of all sizes, particularly on SMEs, which could aid in preventing financial strain and imbalances, while also minimizing the need for policing interventions. Moreover, the market interventions should be proportionate to the size of actors, promoting growth for both SMEs and larger organizations. Regarding SMEs, interviewees also emphasized that the costs of managing a DPP should be manageable, if not entirely free.

Secondly, conditions related to data quality and information management were mentioned. Interviewees highlighted the need for ensuring that the information is correct, up to date, reliable and validated. Some interviewees underscored the importance of a reasonable level of detail of information, and that a DPP should not contain abundant data merely for the sake of data itself. One interviewee strongly highlighted that maintaining a sufficient level of detail will improve the DPP's ability in saving resources and improving efficiency. The interviewee further emphasized the need for a cost-benefit analysis during creating and designing a DPP, to assess the cost-benefit ratio to managing relevant information.

Thirdly, conditions related to standardization involve the need for standardization, for instance, regarding data format, methodology, tools and software. Most importantly, the content of a DPP should be standardized. There is a need for uniform, harmonized and comprehensive approaches. It should also ensure capacities for flexibility of the system, allowing for constant evolving and development. Two interviewees highlighted that the data requirements should not be too restricting and should also take into account potential data blind spots.

Table 10. Conditions of a DPP.

Conditions related to accessibility	Ensuring ease, availability and practicality
	Ensuring data relevance
	Ensuring the realization of benefits for all actors in the value chain
	Ensuring manageable costs, for all sizes of enterprises
	Implementing systematic and organized data collection
	Ensuring proportional market interventions to the size of enterprises
	Ensuring participation of all actors of the value chain, to avoid financial strain and imbalances, and minimize the need for policing interventions
	Ensuring participation of all actors to reach full traceability and transparency
	Ensuring transparent data sharing
	Availability through an existing widespread used software
	Implementation in phases
Conditions related to data quality and information management	Digital product information management
	Information version management
	Verification and monitoring of data
	Ensuring data quality, reliability and validity
	Limit the repeatability of data
	Ensuring the correctness and up-to-dateness of information
	Ensuring a reasonable level of detail in data
Conditions related to standardization	Establishing uniform, harmonized and comprehensive data formats, methodology, tools and software
	Defining the standardization for data formats for consistent information
	Ensuring capacities for flexibility of the system, allowing for constant evolving
	Content of a DPP
	Method of access

4.3.3 Discussion

The results suggest that the main barrier in implementing the DPP is related to business confidentiality and protecting intellectual property, while ensuring traceability and transparency. This is also evident in the literature (e.g. Ducuing & Reich, 2023; Koppelaar et al., 2023; Walden et al., 2021). Moreover, the results indicate that manufacturers are the primary focus concerning this barrier. As also discussed in Section 4.2.2., manufacturers are simultaneously considered as the most crucial source of information, underscoring the significance attributed to manufacturers. Jansen et al. (2022) discusses that the DPP is regarded as a means to gain a competitive advantage, with organizations approaching with a profit-orientated mindset or driven by future regulations. Findings suggest that one incentive for data sharing is, for instance, benchmarking. By ensuring that the DPP will contribute to the growth of companies, and through benchmarking on data sharing, manufacturers may recognize the benefits. Adisorn et al. (2021) proposes as means to reduce the burden of manufacturers by developing an approach, that consolidates the information provided by manufacturers. Herein, manufacturers provide the information once, and the system distributes it to different stakeholder groups based on their specific access rights. However, this may contradict the idea of the DPP being transparent to all stakeholders, affecting the reliability.

The level of detail of data in the DPP is crucial, both in the context of protecting intellectual property and ensuring successful implementation of the tool. An appropriate level of detail that does not violate trade secrets, while maintaining transparency, needs to be found. Findings suggest that a cost-benefit analysis is one approach.

The study suggests that a mandatory approach could significantly maximize the benefits by ensuring the participation of all stakeholders, an essential condition highlighted in the findings. The DPP could then comprehensively realize the various benefits for end-users, resulting in enhanced circularity. As also discussed in Section 4.2.2, the willingness of data sharing could be limited to what current regulations require. Hence, this could underscore the role of regulations, functioning as an enabler of circular economy. Thus, from the perspective of accelerating to a circular economy, making it mandatory could be a viable option. In that case, findings emphasize that regulations must take into consideration the stakeholders' data content needs, while ensuring system flexibility.

The legislation should not interfere too much with the content of a DPP, as findings suggest the content should be market-oriented. The problem concerning regulations, is that the information and its management keeps evolving constantly, whereas legislation and regulations are considered slow tools, often acting as an obstacle rather than facilitating the spread of optimal market practices. However, the legislations are not a problem imposed by the DPP itself.

Data quality is one important factor to be considered for the DPP. It covers many aspects, requiring lots of effort. Findings suggest that one important aspect is how to keep information up to date, which is especially relevant when considering the possible long lifespan of construction products and multiple ownerships of buildings, as also pointed out by Luscuere (2017).

The flexibility of the system was also highlighted, as the data content requirements should not be too restricting in terms of what to include and that it does not ignore blind data spots. This aspect could become more relevant when considering the lifespan of buildings or ensuring the up-to-dateness of product information in the future. Furthermore, as circularity in the construction sector is at infancy and circularity indicators under development, flexibility becomes even more important.

It could be contemplated whether actors in the construction industry could develop a model integrated in a DPP. For instance, models could further generate estimations or statistical predictions based on the accumulated data multiple DPPs could gather. This could include data on e.g. wear and tear, sustained damages and their impact on the lifespan of construction products.

The findings highlight the role of SMEs, who may face barriers in terms of time, financial burdens and IT-expertise. Due to the possible lack of programs, tools and resources, it may put SMEs at a disadvantageous position. As participation from all stakeholders is needed to ensure full traceability and transparency, it is of uttermost importance to involve organizations of all sizes during designing and implementing the DPP. The importance of this is further emphasized by results indicating that ignoring SMEs could lead to financial strain and imbalances. However, due to the scattered survey results regarding whether financing aspects poses specifically as a barrier for SMEs, any conclusions should be drawn carefully.

5 Conclusions

This final section concludes the thesis. First, key conclusions are presented. Then, suggested future lines of enquiry are presented.

5.1 Key conclusions

The main objective of this thesis was to explore the benefits of a DPP for construction products. Furthermore, the aim was to identify the data requirements of key stakeholders as well as the barriers and challenges in implementing the tool. Through an extensive analysis of existing literature, semi-structured interviews and a survey, the research objectives were addressed.

The key benefits of a DPP are rooted in improved traceability, involving enhanced circularity, access to centralized source of information and improved resource efficiency. To realize the potential benefits, the identified data requirements involve manufacturing, usage, end-of-life and life-cycle data. The results suggest that these data types can function as a general guideline, while the more precise content should be tailored to each product group. The potential bottlenecks in successful implementation involve protecting intellectual property while maintaining transparency, and ensuring data quality, including keeping information up to date, which can become especially challenging due to the long lifespan of various construction products. Moreover, the inclusion of organizations of varying sizes is essential to ensure successful implementation as well as full traceability and transparency.

This thesis sheds some light on the perspectives of key stakeholders in the construction industry, contributing to the existing knowledge within a field with scarce research on DPP. The study can provide some practical implementations for future regulations. Firstly, the findings provide insights on the data content needs, suggesting the content should be market-oriented. Moreover, the thesis identifies areas for improvement, concerning the data needs of all stakeholder groups to enhance the overall appeal of a DPP. Secondly, the thesis can offer suggestions for implementing the DPP in phases, with results indicating prioritizing either concrete products or short-lived product groups. Finally, while the thesis identifies the benefits of a DPP, a gap in stakeholder perceptions is identified, necessitating justification of benefits for all actors to ensure a successful employment of the tool.

5.2 Suggestions for further research

The DPP can show to be a valuable tool in the transformation to a circular economy, as it can offer practical and viable solutions for end-users.

Improved resource efficiency and facilitated decision-making can be attributed as its most valuable benefits, considering the direct impact on the outcomes. However, it should be acknowledged that the successful implementation of the DPP is dependent upon its weakest link, with the tool's usability and stakeholder perceptions playing a critical role. Overcoming the barriers is crucial, otherwise, the practicality and efficiency of the tool could be significantly limited. With this perspective, this subsection aims to scrutinize the suggestions for further research.

This thesis primarily underscores the need for additional research in identifying data requirements of each stakeholder group within each construction product supply chain. One consideration is to further add stakeholder groups for different construction product groups, since they may vary between value chains. Furthermore, it is crucial to find an optimal level of detail that adheres to intellectual property while maintaining transparency. Another dimension to consider is to further explore manufacturers' engagement in data sharing and utilization, as they are the primary focus concerning business confidentiality issues.

There is also a need to address the gap in stakeholder perceptions to ensure widespread adoption of the DPP. This involves justifying the benefits for all stakeholders, to enhance the overall appeal of the DPP. For instance, the results imply that stakeholders in R&D and strategy might need different data in the DPP to enhance its appeal. Furthermore, regarding end-of-life management stakeholders, research is needed to determine the practical feasibility of the DPP during demolition.

Considering the phased implementation of the DPP, the study could offer a starting point for future research. Concrete products might be a suitable option, as they have significant environmental impacts. Alternatively, the study also suggests short-lived product groups as an option, to effectively showcase the tangible benefits of the DPP, encouraging end-users for continued use.

Finally, one limitation of the results is the small sample size and constitution. To improve the reliability of the results, one option would be to include additional key stakeholder groups, for instance, to distinguish designers and manufacturers. Furthermore, stakeholders from R&D and strategy were the most represented in this thesis, potentially overshadowing other important groups. Because full traceability and transparency requires participation from all stakeholders, a valuable approach could involve organizing key stakeholder groups based on size. Furthermore, the interview perspectives were focused on Finland, limiting the transferability of interview findings to the rest of the EU. More participants from various EU-countries could enhance the generalizability of results.

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I. Interview guide

1. **Introducing questions**
    a. Could you briefly introduce yourself, and tell me about the organization and your role in the organization?
    b. What is the business model of the organization? What products or services does it offer?

2. **Circular economy**
    a. Is circular economy (CE) or sustainable development a part of your organization's plan?

    If yes:

    i. In what ways? How is it reported, e.g. is it followed up by a sustainability report or by other means?
    ii. Is the organization's CE-strategy and CE-practices prominent in your work task? Please, elaborate.
    iii. What CE-practices from the 9R-framework are involved in your work and in the organization's activities?

    If no:

    i. Why not? Are they planned to be incorporated? When and how?

3. **Data and traceability for circularity**
    a. Where are you now with transparency and traceability in your organization? Is it mostly internal activities/within your organization? How much do you interact with other stakeholders in the value chain?
    b. Does your organization utilize data for the purpose of circularity? In what ways? What kind of data?
    c. Does your organization currently have unused data that could be used to further foster CE practices? What kind of data is it? Is your organization planning to further use this data? Why/Why not?
    d. Are there significant information gaps in your work/role? Are you able to obtain data from other actors in the value chain? How? What kind of data or information are you usually missing?

4. **Benefits of digital product passports**
    a. In your organization, are DPPs planned to be incorporated in the future?

    If yes:

    i. Why? Has your organization already prepared for the use of DPPs? How?

If no:

    i. Has it been considered? What are the reasons for not planning to use DPPs?

b. Do you see potential in using a DPP? What potential does it have?
c. What would be the added value of a DPP in your role/work? At organization-level?
d. What CE practices from the 9R-framework would benefit the most from using a DPP?
e. Are there particular construction product supply chains that would benefit the most from using a DPP? Which construction products? Why and how?
f. In the long run, would using a DPP save time, energy and/or resources in your work/organization, or the opposite?

5. **Content of a digital product passport**
    a. In your work, what data in a DPP would you benefit from? See Table 1.
    b. Does your organization have some data you think other actors in the value chain could benefit from?
    c. As the contents of a DPP is yet undefined, it is unclear whether it should trace the entire value chain of a product, including information on all separate materials pre-manufacturing, or if it should begin tracing from product manufacturing onwards. Would you need to trace pre-manufacturing data of materials, or only trace data starting from the product manufacturing?
    d. According to the data minimization principle for a DPP, in order to improve accessibility and user-friendliness, the contents of a DPP should only include necessary data. Based on this principle:
        i. In your work, what kind of data would be critical to include in a DPP?
        ii. In your work, what kind of data would be less important or not beneficial to include?

6. **Barriers for implementing digital product passports**
    a. From a general point of view, what kind of barriers would there be in implementing a DPP?
    b. In your work and organization, do you think the following aspects act as a barrier for implementing a DPP?
        i. Business confidentiality
            1. What kind of data would your organization be willing to share and what not?
            2. What are the barriers to sharing this data?

3. What would be incentives to make the organization share the needed data?

ii. Time
iii. IT- knowledge
iv. Policy landscape

c. What would be ways or approaches to overcome these barriers?

7. Final questions

Do you have anything to add to the topics discussed during this interview? Is there something else I should know or ask more about? Is there someone else I should consider interviewing?

Table 1. Examples of data groups and associated data.

Manufacturing data The process and its documentation The composition of the product (materials and weights used in each component) Technical data Physical and chemical properties Batch number or other identification	**Usage data** Changes to the product during the use-phase (e.g. parts that have been replaced or repaired) Recorded damages Disposal
End-of-life data Documentation on collection, sorting and treatment Other waste management data Applied recycling method used	**Life-cycle data** Guidelines for storage and usage of the product Information of the environmental impacts SLCA

II. Survey questions

Background information

1. Job title
2. Country of organization
3. Size of organization
    - 0-9 (micro-enterprise)
    - 10-49 (small enterprise)
    - 50-249 (medium-sized enterprise)
    - >250 (large enterprise)
4. 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)
    - 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)
    - Other
5. If you chose "Other" please specify your work role and what your organization represents.
6. How familiar is your organization with digital product passports (DPP)?
    - Our organization already uses DPP
    - Our organization is planning to use DPP
    - Our organization is familiar with DPP, but is not planning to use it
    - Our organization is not familiar with DPP

Benefits of a DPP

7. Statements on benefits in using a DPP.
   Likert scale: Strongly disagree – Disagree – Somewhat disagree – Neither agree nor disagree – Somewhat agree – Agree – Strongly agree
    - Improves traceability and transparency
    - Adds financial benefit and competitive advantage
    - Facilitates planning and procurement
    - Facilitates certification processes
    - Hinders greenwashing

  - Saves time during construction and/or demolition
  - Our organization could benefit from acquiring data from other actors for circularity purposes
  - Our organization does not see any benefits in sharing data with other actors
  - A DPP should be mandatory for all actors in order to reach the benefits
8. In your opinion, which of the following construction product supply chains would benefit the most of a DPP in terms of circularity purposes? Please select at most 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, chip-boards)
    - Plastic products (e.g. tubes, pipes, water barriers)
    - Bricks, tiles, ceramics
    - Aggregates
    - Insulation (including both mineral and non-mineral thermal insulation)
    - Doors and windows
    - Wall systems
    - Roofing and flooring systems
    - Interior products that are normally stripped out before demolition (e.g. HVAC, radiators)
    - Other
9. If you chose "Other", please specify.
10. Please, elaborate on the answers in this section if you want.

Data content requirements of a DPP

11. In your work, do you experience the following data, information or communication gaps?

    Likert scale: Never – Rarely – Occasionally – Regularly – Very often – Constantly – No opinion
    - Lack of data on safety and health hazards
    - Lack of information on environmental impact
    - Lack of data on product testing and performance
    - Lack of material flow data
    - Communication gaps with other stakeholders in the value chain
12. Does your organization currently have unused data within the organization, that could be used to further foster circular practices?

- Yes
- No
- Maybe

13. Please specify, what kind of unused data?
14. Does your organization have some data you think **other actors** in the value chain could benefit from for circularity purposes?
    - Yes
    - No
    - Maybe
15. Please specify, what kind of data?
16. Indicate how relevant these following **product manufacturing data** in a DPP would be for your work.
    Likert scale: Not at all relevant – Slightly relevant – Somewhat relevant – Relevant – Very relevant – I don't know
    - Material contents (physical and chemical properties, hazardous materials, source of materials)
    - Technical data about the manufacturing process
    - Product identification, such as batch number
    - Quality control measures
17. Indicate how relevant these following **usage data** in a DPP would be for your work.
    Likert scale: Not at all relevant – Slightly relevant – Somewhat relevant – Relevant – Very relevant – I don't know
    - Changes made to the product during the use-phase (e.g. parts that have been replaced/repaired)
    - Recorded damages
    - Energy consumption information
    - User and safety manuals including information on assembly, maintenance and disassembly
18. Indicate how relevant these following **end-of-life data** in a DPP would be for your work.
    Likert scale: Not at all relevant – Slightly relevant – Somewhat relevant – Relevant – Very relevant – I don't know
    - Instructions on removing hazardous materials or dismantling of product
    - Recycling or disposal instructions, including EPR-obligations
    - Reporting of collection, sorting, pre-treatment
19. Indicate how relevant these following **life-cycle impact data** in a DPP would be for your work.
    Likert scale: Not at all relevant – Slightly relevant – Somewhat relevant – Relevant – Very relevant – I don't know

- Information on environmental impacts (e.g. GHGs and other emissions)
- Social impact
- Circularity performance (e.g. the Material Circularity Indicator by the Ellen MacArthur Foundation)
- Sustainability certifications

20. Is there any other data that is necessary to include or consider? Please specify.
21. Please, elaborate on the answers in this section if you want.

Barriers in implementing a DPP

22. In your opinion, does the following factors act as a barrier?
    Likert scale: Not a barrier – Minor barrier – A barrier – Major barrier – A significant barrier – No opinion
    - Business confidentiality issues
    - Financing aspects
    - Cultural aspects
    - Lack of resources (for data input and processing)
    - Lack of required IT-knowledge
    - Lack of standardization and framework
23. Does your organization have concerns regarding legal and regulatory aspects?
    - Yes, our organization has significant concerns
    - Our organization has some concerns
    - No, our organization does not have any concerns
    - I do not know
24. In your work, do you see yourself using a DPP?
    - Never
    - Rarely
    - Occasionally
    - Regularly
    - Frequently
    - I do not know
25. Please, elaborate on the answers in this section if you want.

Final questions

26. Do you represent an EU-funded research project (such as ICEBERG, CISUFLO etc.)?
27. If yes, which project?
28. If you have anything to add, please fill in the box below.