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**Elnaz Amia**

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# Identifying Barriers to Implementing Digital Product Passports

**Internal supervisor:** **Dr. Enikő Lencsés**

**Associate Professor**

**Author:** **Elnaz Amia**

**CMITEY**

**Supply Chain Management**

**Full-degree Master**

**Institute/Department:** **Institute of Agricultural and Food Economics, Department of Agricultural Logistics, Trade and Marketing**

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**Elnaz Amia**

**Supply Chain Management, Full-degree Master**

**Institute of Agricultural and Food Economics, Department of Agricultural Logistics, Trade and Marketing**

**Insider subject leader: Dr. Enikő Lencsés**

## Abstract

The urgent demand for sustainable production and consumption approaches has prompted the development of Digital Product Passports (DPPs), planned as essential instruments to enhance transparency and efficiency within the circular economy. However, the adoption of DPPs is challenged by a variety of complex barriers. This thesis explores these challenges, applying Interpretive Structural Modeling (ISM) along with the Delphi Technique to carefully identify and analyze the barriers to widespread DPP implementation. This thesis discovers a detailed hierarchy of barriers, including significant technical complexities, regulatory gaps, and cultural resistance within organizations. These findings are structured into a multi-level model that highlights the essential strategies needed to address these obstacles. By integrating knowledge from industry experts and thorough structural analysis, the study offers strategic recommendations for policymakers and industry stakeholders, aimed at facilitating the integration of DPPs into sustainable business practices. This work not only illustrates the barriers but also provides a collection of researchers' recommendations for leveraging digital technologies to foster a more sustainable and efficient global economy through enhanced, transparent product lifecycle management.

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# 1. Introduction

As global environmental concerns increase, the need for sustainable production and consumption becomes more urgent. Digital Product Passports (DPPs) have emerged as a promising tool to enhance transparency and efficiency within the circular economy. Despite their potential, widespread adoption faces significant barriers. This thesis investigates these challenges, aiming to provide actionable insights for industries and policymakers. By identifying and analyzing these barriers, this study contributes to optimizing the integration of DPPs, thereby supporting sustainable practices across various industries. Following this introduction, the thesis will explore the literature, detail methodologies, present findings, and discuss their implications.

## 1.1Background

The escalating consumption of resources and the subsequent environmental degradation highlight the urgent need for sustainable solutions in product lifecycle management. Digital Product Passports (DPPs), which are in line with the Sustainable Development Goals (SDGs) of the UN, have become a practical instrument to promote responsible consumption and production in the face of growing environmental concerns and a movement towards sustainability. DPPs, using digitalization, aim to enhance transparency and enable efficient resource use by providing detailed information about a product's origin, components, and recyclability.

The importance of DPPs is supported by the concept of the Circular Economy (CE). By emphasizing waste reduction, product lifecycle extension, and recycling, the circular economy (CE) separates economic growth from resource depletion, in contrast to the conventional "take-make-dispose" model. The significance of responsible resource management is not a recent development; it garnered increased attention following Meadows and the Club of Rome's emphasis on the finite nature of our planet's resources in 1972 (Meadows, 1974). This growing awareness, in line with the United Nations' Sustainable Development Goals (SDGs) (United Nations, 2021), has elevated the concept of Responsible Consumption and Production (RCP) to worldwide recognition. RCP emphasizes the importance of efficient resource use, waste reduction, and sustainable practices throughout the production and consumption cycle, aiming to decouple economic growth from resource depletion and environmental degradation. Supporting this concern, the Circular Economy (CE) model seeks to maximize resource utilization by promoting longer product life cycles and sustainable practices(Geissdoerfer *et al.*, 2017; Mallick *et al.*, 2023). Unlike the linear "take-make-dispose" model, the CE focuses on reducing waste and pollution through recycling, reuse, and remanufacturing, thus aligning with RCP goals to foster a more sustainable global economy.

However, the adoption of CE strategies is challenged by a lack of transparency, data sharing, and the need for standardized data and procedures crucial for informed decisions in product design, manufacture, reuse, and recycling (Bocken *et al.*, 2016; Saari *et al.*, 2022). Digitalization, offering precise data on product location, availability, and condition, could significantly support CE implementation by enhancing resource efficiency, minimizing waste, and streamlining processes (Antikainen, Uusitalo, and Kivikytö-Reponen, 2018).

Digital Product Passports (DPPs), proposed by the UK Government (Hm Government, 2018) and explored by the European Commission within the European Circular Economy Action Plan (CEAP), represent a technology-based solution aimed at enhancing circular economy initiatives (EUROPEAN COMMISSION, 2020a, 2022a). DPPs, gaining popularity among policymakers, find applications across industries, facilitating the shift towards more sustainable practices by offering detailed product information, which supports extended product lifespans, waste reduction, and sustainable product creation (Adisorn, Tholen and Götz, 2021; Walden, Steinbrecher and Marinkovic, 2021; Melanie R.N. King, Timms, and Mountney, 2023). Furthermore, by providing information on repairability and spare parts, DPPs serve as a valuable decision-making tool, promoting more efficient use of resources and accelerating the transition to a circular economy(Antikainen, Uusitalo and Kivikytö-Reponen, 2018). The integration of digital intelligence facilitates the dissemination of information, ownership, structure, and various levels of customization, fostering more profound and enduring connections with consumers and end-users. This incorporation of digital capabilities can empower consumers to extend a product's lifespan through improved maintenance, repair, and refurbishment (Melanie R N King, Timms and Mountney, 2023). Similarly, by closely observing a product through its whole lifecycle, businesses can identify significant opportunities for waste reduction, improved productivity, and the production of sustainable products. This approach follows the principles of responsible resource management and contributes to a more sustainable and environmentally friendly framework in production and consumption (Walden, Steinbrecher and Marinkovic, 2021). Additionally, through a broader perspective, by providing information on repairability, spare part availability, and repair guides, Digital Product Passports (DPPs) serve as a central repository for diverse data and decision-making tools. This not only accelerates the transition to a circular economy but also enables more efficient resource utilization (Antikainen, Uusitalo and Kivikytö-Reponen, 2018).

The goal of this thesis is to explore the barriers that prevent DPPs from being widely adopted and to clarify the complicated steps involved in integrating digital solutions for sustainable product lifecycle management. By exploring these challenges, this study seeks to contribute to the discussion on utilizing digital technologies to achieve environmental sustainability goals, offering insights for policymakers, industry stakeholders, and the technology community on facilitating the adoption of DPPs.

### 1.2 Problem statement

The Digital Product Passport (DPP) initiative, aligned with the Sustainable Development Goals (SDGs) of the United Nations, has emerged as a practical tool to promote responsible consumption and production, aiming to enhance transparency and enable efficient resource use. This concept of digital product passports is seen as a one-stop solution for data delivery, aligning with recent legislative proposals (Ducuing, 2023). In exploring the landscape of DPPs, a critical gap emerges in understanding the fundamental requirements and technical complexities involved in an efficient DPP system. Recent investigations highlight the complexity surrounding DPPs, particularly the barriers to integration within the circular economy. Current discussions in both industry and academia, focusing mainly on content and policy, fall short of addressing these foundational technical challenges, suggesting a need for a more in-depth examination of DPP systems (Jansen et al., 2023). However, despite the potential benefits of DPPs, manufacturers face significant challenges in implementing these passports. Some of the primary barriers include a lack of detailed information on product composition, usage, and end-of-life handling, integration complexity, stakeholder resistance, data privacy and security concerns, and the need for standardization of data.

These challenges hinder the adoption of DPPs by manufacturers, which is critical for the realization of a more sustainable, circular economy. Moreover, organizational opposition, employee resistance, and resistance from middle management might prevent small and medium-sized businesses from adopting Industry 4.0 technology. Furthermore, the degree of maturity of a company's digital transformation plays a crucial role in how barriers are perceived (Raj *et al.*, 2020).

DPPs have been proposed and explored as a technology-based solution aimed at overcoming these challenges, enhancing circular economy initiatives, and supporting the transition towards more sustainable practices across industries. However, the path to their widespread adoption is not without obstacles. Lack of industry-specific regulations, prohibitively high implementation and maintenance costs, a lack of urgency in adopting new technologies, and a deficiency in digital skills and capabilities present significant barriers to this digital transformation of supply chains (Agrawal, Narain and Ullah, 2020). In the context of a circular economy, the adoption of digital technologies like product passports can enhance sustainability by facilitating the storage and traceability of product data (Lövdahl, Hallstedt and Schulte, 2023). Nonetheless, to promote the adoption of circular economy measures effectively, challenges such as the need for product customization and overcoming technological barriers must be addressed(Bag and Pretorius, 2022). This multifaceted landscape illustrates the complex relationship between technological innovation, regulatory frameworks, industry readiness, and the overarching goals of sustainability and circular economy. DPPs have the potential to transform product lifecycle management and promote a more sustainable future; however, there are difficulties in the way of their implementation requiring collaborative efforts from the technology community, industry stakeholders, and policymakers. To fully realize the promise of digital product passports and move closer to a more efficient and sustainable global economy, it will be necessary to address such barriers through cooperative efforts, creative solutions, and proactive policymaking.

In conclusion, the barriers to adopting digital product passports are diverse and encompass issues related to skills, costs, urgency, guidelines, resistance, and technological challenges. Overcoming these barriers is crucial for the successful integration of digital technologies in supply chains and the transition towards a circular economy. Addressing these barriers requires a comprehensive understanding of the obstacles and an exploration of the technical and regulatory complexities involved in DPP implementation.

This thesis aims to contribute to the ongoing discourse on digital technologies' role in achieving environmental sustainability goals, providing valuable insights for policymakers, industry stakeholders, and the technology community. By thoroughly examining the multifaceted challenges associated with DPP adoption, this study seeks to identify effective strategies for overcoming these barriers, thereby facilitating the broader integration of DPPs into sustainable product lifecycle management practices.

### 1.3.Purpose

The introduction of the Digital Product Passport (DPP) program, driven by the Sustainable Product Regulation (SPR) proposal from the European Commission, is a significant step forward in improving product sustainability, traceability, and transparency over the course of the product lifecycle. This initiative is especially crucial for sectors with significant environmental impacts, with an initial focus on consumer electronics, batteries, and apparel, set to be implemented in the first phase by 2026. The anticipated deployment of DPPs signifies a transformative era in product management, promising to revolutionize how products are designed, produced, used, and recycled. However, despite the significant potential benefits, the implementation path for manufacturers is complicated with substantial barriers. These include, but are not limited to, challenges related to the accessibility of detailed product information, the complexity of integration processes, stakeholder resistance, data privacy and security concerns, and the critical need for standardizing data protocols.

The goal of this master's thesis is to thoroughly investigate the obstacles that would be faced when implementing Digital Product Passports. The main goal is to fully analyze these obstacles to provide insight into the complexities that prevent digital solutions from being seamlessly integrated into sustainable product lifecycle management. This study attempts to provide a detailed understanding of the barriers to successful DPP adoption by carefully examining the various problems that could be encountered. By examining these barriers, the thesis seeks to provide deep insights, thereby paving the way for creative solutions to facilitate the widespread adoption of DPPs. The clarification of these challenges and the exploration of possible solutions will not only enrich the academic discussion on applying digital technologies for environmental sustainability but also provide an overview for stakeholders to navigate the complexities associated with DPP implementation. As a result, this thesis attempts to clarify the current state of applying these digital technologies and their potential role in achieving environmental sustainability goals. It emphasizes the importance of removing current obstacles to fully realize the promise of digital product passports.

### 1.4. Research Questions

- What are the strategic barriers to the implementation of Digital Product Passports (DPPs) by manufacturers?
- What strategies could be employed to overcome the barriers to Digital Product Passport implementation?

### 1.5. Research objectives

- To identify and catalog the barriers to DPP implementation through an extensive literature review and expert insights.
- To analyze the interrelationships between the identified barriers.
- To prioritize the barriers according to their impact on DPP implementation.
- To model these barriers.

# 2 Literature review

## 2.1 The Concept of Digital Product Passports

### 2.1.1 Definition and Objectives

Digital Product Passports (DPPs) represent a cutting-edge approach created to enhance circular economy methodologies by promoting greater transparency, resource efficiency, and sustainability throughout a product's lifecycle. These passports function as comprehensive digital records that present essential data about a product's origins, its constituent materials, and its potential for recyclability and reuse. Such detailed transparency empowers consumers to make well-informed purchasing decisions, thereby encouraging the market toward more sustainable consumption and production models. The primary objective of DPPs is to improve the flow of critical product-related information among all stakeholders—manufacturers, consumers, and waste management organizations. This facilitates a well-coordinated management of products from their inception through to their end-of-life phase, ideally into the recycling or reuse path. By enabling this seamless information exchange, DPPs play an essential part in reducing waste and environmental impact, extending the useful life of products, and optimizing material use. Moreover, the implementation of DPPs aligns perfectly with the goals of the circular economy, which seeks not only to minimize waste but also to prevent economic growth from excessive resource consumption. This approach ensures that products are designed and utilized in a manner that promotes resource conservation and sustainability. Furthermore, DPPs enable the enforcement of environmental regulations and standards by offering a dependable and easily accessible data foundation, which helps achieve regulatory compliance and improve the sustainability of products. DPPs essentially aim to establish a closed-loop system that facilitates more efficient tracking, management, and recycling of items, therefore supporting a more sustainable business model. The broader adoption of DPPs could lead to significant advancements in how products are perceived and managed throughout their lifecycle, promoting a shift towards a more sustainable and resource-resilient society.

### 2.1.2 Historical Development

Digital product passports, linked to environmental policy, technological progress, and global sustainability goals, have evolved significantly over time. The historical development of Digital Product Passports (DPPs) has been connected to the constantly changing dynamics of environmental policy, technological progress, and global sustainability goals. DPPs originated from preliminary ideas in the 2000s and were initially a part of larger initiatives to enhance product information and supply chain transparency for environmental compliance. With the development of cloud computing, big data analytics, and the Internet of Things, these ideas gradually transformed into more sophisticated systems capable of tracking extensive product data across entire lifecycles(Schaubroeck, Dewil and Allacker, 2022). The Wuppertal Institute has provided a new, thorough definition of DPP, defining it as a data collection that includes a list of the components, materials, and chemical compounds included in a product along with information on repairability, replacement parts, and disposal instructions (Walden, Steinbrecher and Marinkovic, 2021). According to Luigi Panza (Panza, Bruno and Lombardi, 2023), DPP is a crucial tool in Industry 5 which serves as a comprehensive digital product identity, supporting sustainability, circular economy transitions, resource efficiency, and extended product lifespans. Aligned with Industry 5.0 principles, the DPP contributes to a human-centric, sustainable, and resilient approach, distinguishing itself from the efficiency-focused Industry 4.0. Digital Product Passports (DPPs) significantly enhance product lifecycle management by providing structured information on components, origin, and environmental and social impact. This information supports the circular economy and promotes a resource-efficient approach (Jansen *et al.*, 2023). DPPs provide a centralized repository of data, facilitating better decision-making and enhancing circularity. DPPs contribute to data-driven circular economy policies by establishing data standards and enabling data-based decision-making (Ducuing, 2023).

The integration of DPPs into circular economy frameworks became significantly greater in the 2010s, influenced by global movements towards sustainability and resource efficiency(Mulhall *et al.*, 2022). The European Union's revitalization of its Circular Economy Action Plan in 2015, and later the European Green Deal in 2019, provided a regulatory backbone that pushed for the adoption of DPPs (Götz, 2022). These policies required comprehensive lifecycle data to be accessible, aiming to minimize waste and maximize resource reuse through better product design and end-of-life management (Jansen *et al.*, 2023). The significance of DPPs has continued to rise, as recent regulations crafted by the European Commission have been specifically designed for incorporating eco-design requirements into the textile component of sustainable product development (Adisorn, Tholen and Götz, 2021). DPPs have a major role in enhancing these eco-design frameworks, ensuring that all stakeholders—from manufacturers to consumers and regulators—have the necessary data to make informed decisions about products(Rumetshofer and Fischer, 2023).

Research across various sectors, such as the built environment, has demonstrated the potential of digital platforms to manage material passports effectively, highlighting the use of DPPs in projects like the EU-funded BAMB. Material passports, digital platforms, and additive manufacturing are key digital technologies that facilitate the transition to a circular economy in the built environment by enabling resource tracking, reuse, and sustainable material management (Çetin, De Wolf and Bocken, 2021). These initiatives highlight how important digitization is to the coordination of material and information flows that are necessary for effective circular economy principles (Almusaed *et al.*, 2021). For instance, standardizing data collected from Digital Passports can address key business concerns about reusable packaging, such as affordability, health and safety compliance, reputational concerns, and competition. Open data standards and Digital Passports could transform packaging from waste to asset, enabling a shift towards a more cooperative Circular Economy (Ellsworth-Krebs *et al.*, 2022a). In addition, the application of DPPs has expanded beyond traditional products to include emerging categories like battery passports, which address specific data governance challenges and enhance transparency across the value chain (Berger, Schöggl and Baumgartner, 2022; Ducuing, 2023). This evolution shows the potential of DPPs to serve as comprehensive repositories of lifecycle data, facilitating a more sustainable economic model across industries.

As digital product passports become more established within industry practices, they not only promote transparency and traceability but also enable businesses to align more closely with sustainable and circular economy objectives. By providing a detailed view of a product’s environmental footprint and fostering a deeper understanding of material efficiencies, DPPs help companies strategically design more sustainable solutions, leveraging tools like the EU's Product Environmental Footprint method (Lövdahl, Hallstedt and Schulte, 2023).

The development of DPPs reflects a significant shift towards a more interconnected and environmentally conscious approach to product management. This shift is not only crucial for achieving global sustainability objectives but also important in informing consumer choices and regulatory strategies in the increasingly digital and resource-constrained world. The ongoing enhancement of DPP frameworks and their integration into global standards will likely continue to influence how products are designed, used, and recycled in the future, fostering a resilient, circular economy that benefits all stakeholders.

**2.2 The Role of DPPs in Achieving Sustainable Development Goals (SDGs)**

The Sustainable Development Goals (SDGs) established by the United Nations in 2015 are important turning points in the effort to achieve global sustainability. They represent a collective vision for fostering dignity, peace, and prosperity for people and the planet, both in the present and future. A crucial component within these goals is the concept of a Circular Economy (CE), which is particularly integral to the fulfillment of SDG 12: Responsible Consumption and Production. This goal supports the sustainable management and efficient use of our natural resources and encourages recycling and waste reduction across industries, businesses, and consumers (United Nations, 2015) (United Nations, 2015).

The philosophy of the circular economy, tracing back to Kenneth Boulding's seminal "The Economics of the Coming Spaceship Earth" in 1966, views the world as a closed system, with limited capacity for waste absorption and resource extraction. Boulding's insights pointed out the finite nature of our planet's resources and the pressing need to integrate economic activity within these ecological limitations (Kenneth E. Boulding, 1966). The concept of the circular economy (CE) aligns with Boulding's insights, supporting a cyclical approach inspired by natural ecosystems. Gaining popularity in the late 1970s, CE presents a viable alternative to the current linear model, offering economic, social, and environmental benefits. Stahel and Reday in pioneering the study of the circular economy elaborated on its potential benefits in terms of economic, social, and environmental sustainability. CE’s principles focus on closing the loop through continuous resource cycling and reusing, minimizing waste generation, and optimizing scarce resource consumption (Stahel, 1981). This acknowledgment prompts a critical transformation in how we approach resource management and economic practices. By keeping resources in use for as long as feasible, extracting the most value from them while in use, and recovering and regenerating goods and materials at the end of each service life, it marks a shift from the classic linear model of "take, make, dispose." Not just Goal 12 but several other SDGs are strongly connected to this model. It supports the reduction of water waste, for example, which helps achieve Goal 6 (Clean Water and Sanitation), Goal 7 (Affordable and Clean Energy) through resource efficiency, and Goal 13 (Climate Action) through waste and emission reduction (United Nations, 2015; Geissdoerfer *et al.*, 2017; Schröder, Lemille and Desmond, 2020).

The Circular Economy is believed to be supported by the development of transparency and expertise in assets and products, including data on their location, condition, and accessibility. Digitalization may accelerate the transition to a more sustainable circular economy (Bocken et al., 2016; Ellen Macarthur, 2012). Facilitating interaction, cooperation, and co-creation with stakeholders, including customers, digitalization empowers businesses to operate more efficiently, reduce waste, promote product longevity, and lower transaction costs, contributing to a more resource-efficient circular economy(Antikainen, Uusitalo and Kivikytö-Reponen, 2018). Advanced technologies such as artificial intelligence, 3D printing, IoT, and online platforms optimize production and extend product lifecycles. The adoption of digital technologies, such as online marketplaces and the Internet of Things (IoT), enables the implementation of service-based business models, such as Products as a Service (PaaS), which allows consumers to purchase the desired services (e.g., lighting, mobility, or healthy food) rather than just the equipment or products (e.g., lamps, cars, or pesticides). This approach promotes the smarter use of resources by reducing the demand for continuous production and encouraging product longevity, reusability, and sharing (Hedberg and Šipka, 2021). TagItSmart is a smart tagging system that allows all involved parties, from manufacturers to customers and recyclers, to track products and provide additional information using QR codes. This includes guidance on recycling methods and locations(Srdjan Krčo, 2019). Integrating CE principles into global economic systems poses both challenges and opportunities. On the one hand, transitioning to a CE requires overcoming significant barriers, including technological limitations, regulatory hurdles, and the need for substantial shifts in consumer behavior and business models. On the other hand, it presents an opportunity to drive innovation, create economic growth, and deliver on environmental sustainability goals. The development and implementation of DPPs can play a critical role in overcoming these challenges by enhancing transparency, enabling informed decision-making, and fostering a more sustainable and efficient use of resources.

While integrating CE into the global economic systems presents numerous challenges—technological, regulatory, and behavioral—the opportunities for innovation and sustainable growth are significant. Digital Product Passports (DPPs) stand out as a critical innovation to surmount these challenges. By ensuring transparency and informed decision-making, DPPs promote sustainable consumer choices and resource-efficient practices throughout the product lifecycle, thereby aiding the achievement of SDG 12 and other sustainability goals.

The European Green Deal's ambitions for sustainability are increasingly tied to the transformative power of digitalization, seen as a key enabler for lowering emissions and promoting resource efficiency. Achieving these objectives requires the "Twin Transition," which includes digitalization and the transition to a sustainable, climate-neutral European economy(CISL., 2020). A critical aspect of this transition is the utilization of Digital Product Passports (DPPs), which provide a digital record of a product's lifecycle, enhancing supply chain accountability, traceability, and transparency. Providing a comprehensive digital framework, DPPs encourage circularity, data-driven innovation, and informed decision-making, addressing the information inaccessibility in current linear economies due to the lack of standardized protocols throughout the supply chain phases (Kristoffersen *et al.*, 2020).

Figure 1 illustrates the role of Digital Product Passports (DPPs) in the journey of sustainable development, setting the foundation for a new era of product lifecycle management. This graphical representation clearly illustrates the product's journey from inception, through usage, and toward renewal or repurposing. At the core of this lifecycle lies the DPP—a digital database that documents detailed information about each phase of the product's existence.

The Beginning-of-Life stage indicates the conception of the product, where material providers and designers work in together, followed by manufacturers and subcontractors who bring the idea to completion. The Middle-of-Life phase sees the product entering the market through logistics and resellers, reaching end users who rely on spare part providers and service providers to maintain the product's utility However, the most transformative phase is the End-of-Life stage, where products are not simply discarded but reintroduced into the economic flow through recycling, remanufacturing, and reuse, embodying the essence of the Circular Economy (Hazen, Mollenkopf and Wang, 2017). This stage, involving recycling, remanufacturing, and reuse, is where the initial purpose of the Circular Economy materializes, displaying a world where waste is a concept of the past and resources are constantly looped back into usage. Remanufacturing is an essential component in implementing the concepts of the circular economy since it enables the reproduction of products without converting them into raw materials, saving resources and maintaining the value of the goods themselves (Nakajima *et al.*, 2024). Through remanufacturing, natural resources are preserved, landfill waste is reduced, and opportunities for skilled employment are created(Hofmeester and Eyers, 2023).

The Digital Product Passport (DPP) plays a crucial role in integrating these lifecycle stages into a coherent and transparent journey. It enables stakeholders at each stage to access critical information, facilitating decision-making processes that are environmentally sound and economically viable. By tracking the journey of a product through its DPP, every stakeholder—from the designer to the recycler—is empowered with the knowledge to optimize their part in the lifecycle (Ji *et al.*, 2022). Consumers can make more informed choices, businesses can improve their resource efficiency, and economies can thrive while minimizing their ecological footprint (Voulgaridis *et al.*, 2023).

The DPP, thus, is not just a tool but a model, redefining the value chain of products in alignment with the Sustainable Development Goals, leading us toward a future where sustainability and progress go hand in hand.

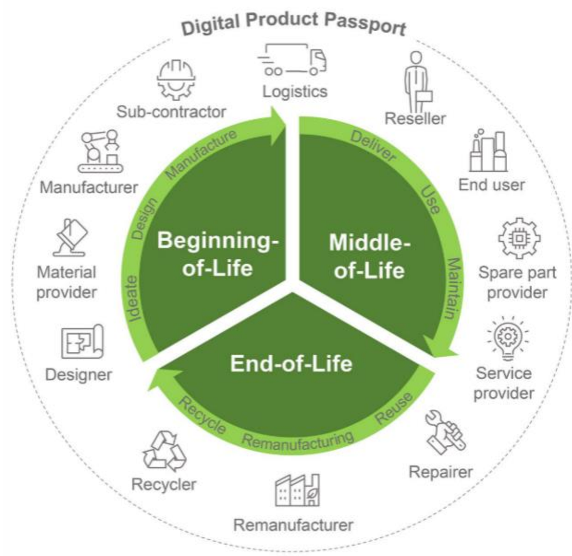


**Figure 2-1** Digital Product Passport (Saari *et al.*, 2022)

### 2.3 Key Benefits of DPPs

The adoption of Digital Product Passports (DPPs) offers a wide range of benefits that span across various stakeholders including industries, consumers, and regulatory bodies. These benefits not only promote a more transparent and sustainable business environment but also empower consumers with the knowledge they need to make environmentally and socially responsible choices. For industries, DPPs enhance efficiency and traceability within the supply chain, promoting resource conservation and innovative business models that align with circular economy principles. Consumers benefit from increased transparency and access to detailed product information, which enhances trust and facilitates informed purchasing decisions. Meanwhile, legislators gain an effective instrument for ensuring compliance with environmental standards, which is critical in the global effort to promote sustainable development. Together, these advantages highlight the transformative potential of DPPs to revolutionize product lifecycle management and support the transition towards a more sustainable and circular global economy. Below is an in-depth explanation of these benefits, illustrating how each stakeholder group stands to gain from the implementation of DPPs:

- Industry Benefits

    - Enhanced Circularity and Resource Efficiency: Industries can manage resources more effectively through improved recycling, refurbishment, and remanufacturing, leading to reduced waste and extended product lifespans. This transition to a sustainable and circular economy requires a fundamental change in approach to resource management and product lifecycles. DPPs provide detailed information about a product, listing master data (product, manufacturer, composition, substances of concern, toxicity and sourcing) and new data (use, modification, maintenance, and wear and tear), enabling businesses to optimize resource utilization, minimize waste generation, and extend product lifespans (Kristoffersen *et al.*, 2020). Such digital data management might facilitate the development of circular economy strategies, such as refurbishment, remanufacturing, and resource recovery programs (Jensen *et al.*, 2023). Providing extra layers of reliable product information about recycled content and raw materials, DPPs can help with data availability and transparency when improving circular designs and practices, including recycling by end consumers (Götz, 2022). They can create innovative circular economy services such as resource recovery plans, remanufacturing initiatives, and product-as-a-service models by utilizing DPP data (Kristoffersen et al., 2020). They can also preserve value and minimize waste by enabling the circular economy to be used to reuse, repair, remanufacture, and recycle products (Jensen et al., 2023). Digital Product Passports (DPPs) significantly enhance resource efficiency and contribute to waste minimization by facilitating several key processes. Firstly, they enable the tracking of the origin of critical raw materials, ensuring that these materials are not sourced from conflict areas and that their extraction methods are environmentally friendly. This traceability helps prevent the use of non-sustainable raw materials in products, thereby reducing waste. Additionally, DPPs provide detailed product composition information that can improve the recycling processes, ensuring that essential raw materials are reused in a way that maximizes their value and further contributes to waste reduction. Furthermore, DPPs enable resource optimization and increase energy efficiency through circular economy practices throughout the entire value chain (Götz, 2022). Digital Product Passports (DPPs) significantly enhance resource efficiency and contribute to waste minimization by facilitating several key processes. Firstly, they enable the tracking of the origin of critical raw materials, ensuring that these materials are not sourced from conflict areas and that their extraction methods are environmentally friendly. This traceability helps prevent the use of non-sustainable raw materials in products, thereby reducing waste. Additionally, DPPs provide detailed product composition information that can improve the recycling processes, ensuring that essential raw materials are reused in a way that maximizes their value and further contributes to waste reduction (Walden, Steinbrecher and Marinkovic, 2021). DPPs drive resource optimization and enhance energy efficiency across the entire value chain; for instance, they play a critical role in transitioning packaging systems from disposable to reusable and refillable solutions. This shift not only addresses the pressing issue of packaging waste but also redefines packaging as a valuable asset rather than mere waste, supporting the broader adoption of circular economy practices (Ellsworth-Krebs et al., 2022).

- Supply Chain Transparency: Digital Product Passports (DPPs) significantly enhance supply chain transparency by providing comprehensive product data from origin to end-of-life, thus improving traceability and enabling industries to optimize production and management processes. By facilitating the exchange of data and information among supply chain participants, DPPs ensure a more transparent view of the product’s origin, manufacturing processes, components, materials used, and environmental impact. Additionally, they prevent data loss throughout a product's lifecycle by promoting a centralized information flow among stakeholders—a crucial step for maintaining the integrity of environmental data (Saari et al., 2022). DPPs also support the circular economy by enabling the reuse, repair, remanufacture, and recycling of products, thereby preserving value and minimizing waste (Jensen et al., 2023). Moreover, the data collected via DPPs aids in optimizing product design for circularity, identifying resource recovery opportunities, and developing targeted policies that incentivize sustainable consumption and production (Koppelaar et al., 2023). They facilitate the creation of innovative circular economy services, such as resource recovery plans, remanufacturing initiatives, and product-as-a-service models, utilizing the detailed data provided by DPPs (Kristoffersen et al., 2020). This systematic sharing of open data helps break down organizational silos and fosters a shared understanding of product lifecycles and environmental impacts (Panza et al., 2023). Consequently, stakeholders—including producers of raw materials, manufacturers, retailers, and consumers—can collaborate more effectively to achieve common sustainability goals. Through enabling comprehensive information sharing across the value chain, DPPs strengthen a cooperative approach to sustainability and drive the shift towards improved sustainability practices in value chains.

- Consumer Benefits
  - Empowered Consumer Choices: DPPs offer consumers detailed product information, enhancing their ability to make informed purchasing decisions based on environmental and social impacts. By offering information about the materials used, the ecological footprint, and the social impacts associated with products, DPPs enable consumers to make more informed purchasing decisions, which can lead to a shift towards more sustainable consumer behavior (Walden, Steinbrecher and Marinkovic, 2021). DPPs play an essential role in empowering consumer decision-making by educating them about the sustainability aspects of products.

  - Increased Transparency: Digital Product Passports (DPPs) substantially enhance transparency within the circular economy by providing detailed information about products directly to consumers. These innovative tools not only allow consumers to access comprehensive data regarding product origins, manufacturing processes, and the environmental footprint, but they also build trust and promote responsible consumption patterns. This comprehensive understanding of a product’s lifecycle allows consumers to see all aspects of a product's impact, further reinforcing the principles of the circular economy. The extensive data provided by DPPs includes detailed information on every phase of a product's life, making these passports a central repository for information delivery. This capability aligns well with recent legislative efforts aimed at facilitating consumer access to essential product information, thereby enhancing transparency and accountability in product manufacturing and disposal processes (Ducuing, 2023).

- Regulatory and Policy Maker Benefits

Digital Product Passports (DPPs) offer substantial benefits to regulators and policymakers by enhancing regulatory compliance and enforcement. By providing a reliable data foundation, DPPs streamline compliance processes, enabling easier adherence to environmental and safety standards, and allowing regulators to monitor compliance more effectively (Kristoffersen et al., 2020). Furthermore, the detailed product lifecycle information available through DPPs assists in identifying non-compliance and supports the development of targeted policies to close regulatory gaps and advance industry standards (Jensen et al., 2023; Götz, 2022). This integration reinforces regulatory frameworks, facilitating a more adaptive and reliable approach to managing industry changes and maintaining high safety and sustainability standards (Panza et al., 2023). The European Commission is actively enhancing eco-design requirements for sustainable products and the Circular Economy, with the development of a Digital Product Passport (DPP) in progress. This passport aims to establish standardized digital fingerprints for circular economy data related to products, aligning with the EU's sustainability objectives (Mulhall *et al.*, 2022).

**2.4 Challenges:**

The adoption of Digital Product Passports (DPPs) presents an innovative approach to managing product lifecycles; however, this transformation is not without a variety of challenges associated with their development and implementation.

- Standardization and Definition Challenges

Lack of Standardized Definition: The lack of a universally accepted definition for Digital Product Passports (DPPs), as noted by Guido Van Capelleveen, presents significant challenges for their broad adoption and effective implementation across various industries and geographical regions. The absence of a clear, universally agreed-upon framework complicates the ability of stakeholders—ranging from manufacturers to regulators—to consistently understand and correctly apply the principles and practices associated with DPPs. This ambiguity can result in inconsistencies in how DPPs are designed and used, potentially reducing their effectiveness in enhancing transparency and sustainability within supply chains (van Capelleveen *et al.*, 2023). These differences may result in a disorganized strategy, where various organizations might interpret or apply DPPs in ways that are not only inconsistent but also unfavorable to the objectives of setting international sustainability standards. The concern regarding standardization aims to establish industry-wide norms for exchanging product circularity data, thereby enhancing transparency and efficiency throughout the supply chain (Mulhall *et al.*, 2022).

- Data Management and Integration Challenges
  - Complex Data Integration: Integrating a comprehensive set of data across a product's entire lifecycle—from the sourcing of raw materials to the final product—presents substantial technical challenges. This process involves the collection, organization, and analysis of vast quantities of data, which must be managed and synchronized across different platforms and stakeholders. Effective data management is crucial for maintaining the integrity and usability of the data, which in turn supports compliance with environmental regulations and fosters a transparent market where information flows smoothly between all parties involved (Götz, 2022; Adisorn et al., 2021).

  - Data Ownership and Privacy: The issue of who owns the data and how it is safeguarded is a critical concern, especially as the use of Digital Product Passports (DPPs) expands. Determining data ownership involves navigating complex legal landscapes and resolving differing international laws and regulations. Privacy concerns must also be carefully managed to protect sensitive information while maintaining a high degree of transparency, a balance that demands sophisticated legal and technical solutions. This balance becomes particularly challenging as transparency requirements increase, necessitating the disclosure of comprehensive data that could potentially include confidential or sensitive business information. Furthermore, the integration of reliable global data standards is essential. Such standards would not only protect sensitive information from unauthorized breaches but also ensure that it remains accessible to legitimate stakeholders across the value chain. Implementing these standards requires a coordinated effort among international regulatory bodies to create uniform guidelines that address data encryption, access controls, and regular audits (Guth-Orlowski, 2021). Effective data management is essential not only for compliance with environmental regulations but also for fostering a transparent marketplace where data flows smoothly between stakeholders. For this to be feasible, several considerations need to be addressed, including ensuring data availability and accuracy, clarifying data ownership, defining access rights, and improving coordination among businesses within the supply chain, regulatory authorities, and consumers (Durand et al., 2022).

- Technological and Operational Challenges
  - System Complexity and Usability: System Complexity and Usability: The technological integration required to implement Digital Product Passports (DPPs) can lead to complex systems that are vulnerable to errors or failures. To maximize the environmental benefits of DPPs and ensure their broad usability, these systems must be user-friendly, providing easy access for all stakeholders, particularly consumers. This is crucial because complex functionalities could overwhelm consumers, thereby weakening their ability to make informed choices and increasing the risk of product misuse or neglect(Coatanroch *et al.*, 2022). The requirement for reliable data management systems is crucial due to the extensive tracking DPPs involve, which includes monitoring usage patterns, repairs, and the product's end-of-life disposal. Throughout a product's lifecycle, these systems must manage not only the volume but also the diversity and the rapid generation and updates of data. Integrating this vast amount of data into a single, easily readable, and accessible passport presents significant logistical and technical challenges. This accessibility involves how well a product or system can be used by people with varying capabilities to achieve specific goals within a given context. Ensuring diverse access levels is vital for transparency, but managing access authorizations can be complex, particularly when it involves sensitive information that might be considered proprietary, such as details about composition or supply chain processes. These issues, along with challenges related to data ownership and access rights, pose substantial barriers to the adoption of DPPs (Rumetshofer and Fischer, 2023). Effective implementation of DPPs thus requires not only technological innovation but also careful consideration of usability and data security to ensure they meet the needs of all users while protecting sensitive information.

  - Flexibility and Adaptability: In rapidly changing global markets, DPP systems must be flexible enough to accommodate updates and changes without substantial services. This requires modular and scalable solutions that can be adapted as new requirements emerge or as the supply chain evolves. The need for such flexible systems highlights the importance of forward-thinking design and development strategies that can accommodate future growth and change (Berg et al., 2022; Guth-Orlowski, 2021).

- Financial Challenges

  The initial setup and ongoing maintenance of DPP systems can be costly, posing a significant financial barrier, particularly for SMEs, which often face difficulties in accessing the necessary capital to invest in new technologies and sustainable practices. These expenses include not only the direct costs of software and hardware but also the training and process re-engineering required to integrate DPPs into existing systems. The following financial burdens are further exacerbated by the need to continuously innovate and implement complex digital solutions that are essential for staying competitive in a rapidly evolving market. Such financial demands can strain resources and deter smaller companies from adopting this potentially transformative technology (Linsner et al., 2021; Hallstedt et al., 2020). Therefore, while the adoption of DPPs is critical for enhancing product safety and lifecycle management, the associated financial demands place a significant burden on SMEs, potentially limiting their ability to fully engage with and benefit from these advanced technological systems.

- Regulatory and Compliance Challenges

  Compliance with legal obligations, such as the European Commission's 'Proposal for the new Ecodesign for Sustainable Products Regulation' (ESPR), Extended Producer Responsibility (EPR), and the 'right to repair' legislation, becomes imperative for the development and implementation of DPP systems. These regulations are designed to ensure that DPPs adhere to the highest standards of sustainability and contribute effectively to circular economy practices. For instance, the ESPR aims to set broad ecodesign requirements that ensure products are designed to be durable, repairable, and recyclable, aligning perfectly with the goals of DPPs to enhance product lifecycle transparency and sustainability. Similarly, EPR schemes require producers to be responsible for the collection, recycling, and disposal of products at the end of their life, reinforcing the circular nature of the DPP framework. The right-to-repair legislation also plays a crucial role by ensuring that consumers have the ability to repair products, thereby extending their lifespan and reducing waste. Each of these legislative frameworks not only supports environmental objectives but also places a regulatory onus on companies to adapt their products and business models to meet these new demands (Jansen et al., 2023).

## 2.5 Industry Applications

### 2.5.1 Electronics Industry

The introduction of Digital Product Passports (DPPs) has revolutionized the way product lifecycles are managed and sustainable optimization in the electronics industry. This initiative, particularly powered by the European Union, focuses on integrating DPPs within electronic devices as a strategic approach to enhancing repairability, extending product lifespans, and consequently reducing the volume of electronic waste—a significant environmental concern. They play a vital role in the circular economy by providing digital identities to physical products, tracking their lifecycles, and offering information on technical specifications, usage instructions, and repair details (Walden, Steinbrecher and Marinkovic, 2021; Voulgaridis *et al.*, 2023). The EU's instructions to implement DPPs in this sector are part of a broader effort to promote circular economy practices, which are essential in addressing the rapid obsolescence commonly associated with electronic goods (European Commission, 2020). E-waste is the fastest-growing solid waste stream in the world (1). In 2019, an estimated 53.6 million tonnes of e-waste were produced globally, but only 17.4% was documented as formally collected and recycled (World Health Organization (WHO), 2023). Developing a digital passport for electronic products involves generating and storing data about the product, its design, and production procedures at each lifecycle stage (Donetskaya and Gatchin, 2021). This digital passport serves as a comprehensive record that can aid decision-making processes and support sustainability assessments throughout the product's lifecycle. Moreover, the standardization of digital fingerprints, such as the Product Circularity Data Sheet, is essential for maintaining consistency and accuracy in the data shared through digital product passports(Mulhall *et al.*, 2022). However, the sector faces challenges including the need to ensure the security of sensitive product data—a critical issue in an era where data breaches are prevalent. There is also substantial resistance from manufacturers who are concerned about disclosing proprietary information that could potentially affect their competitive advantage.

### 2.5.2 Battery Industry

The global battery industry is experiencing a significant transformation due to increased demand for batteries and electric vehicles (EVs). While the shift toward greener transport is positive, it emphasizes the need for more sustainable and transparent battery value chains. The complexity of battery value chains, including the mining and refining of raw materials, poses challenges that must be addressed. Digital Product Passports (DPPs) have been notably beneficial to the battery business, especially in relation to electric vehicles (EVs). These tools are critical in enhancing the traceability of materials and streamlining the recycling process—key aspects that are essential as the EV market continues to expand rapidly. Responsible sourcing of critical raw materials, such as cobalt and lithium, is crucial, and efforts are being made to improve socio-environmental standards in production (World Economic Forum, 2023). Estimations indicate that by 2030, EV sales could account for 30% of all new car sales, underscoring the urgency and importance of establishing a robust, sustainable battery value chain (European Battery Alliance, 2021). The importance of DPPs in the battery sector stems primarily from the need to address the ecological and economic challenges posed by battery production and disposal. Batteries for electric vehicles, such as lithium-ion batteries, involve complex chemistries and utilize rare earth elements and other critical raw materials that are environmentally sensitive and often sourced from geopolitically unstable regions. This complexity not only makes the manufacturing process complex but also presents significant challenges in recycling these materials efficiently at their end-of-life. Furthermore, the lifecycle management of EV batteries is complicated by the need for precise and reliable data to ensure that all materials are responsibly sourced, used, and recycled. DPPs facilitate this by providing a clear and transparent record of the source of raw materials, production processes, and the chain of control throughout the battery's life (Gallina *et al.*, 2023). This degree of traceability is essential for verifying that the materials are recycled and that the recycling process complies with strict environmental regulations. Overall, the integration of digital product passports in the battery industry is seen as a crucial step towards enhancing transparency, traceability, and sustainability. By leveraging digital solutions, stakeholders can better track products, exchange information, and contribute to the development of circular and sustainable value chains. Data from the Fashion for Good initiative in 2022 indicates that while awareness is high, actual consumer preference for sustainable products converts at a significantly lower rate, underscoring the need for ongoing education and transparency efforts.

### 2.5.3 Textile Industry

Based on the latest research by the European Parliamentary Research Service (EPRS) the textile and fashion industries are currently struggling with three major challenges. Ecologically, these sectors are criticized for their significant environmental impact, characterized by the use of non-renewable resources and high levels of water and land consumption. Since the popularity of fast fashion has increased the amount of clothing produced, which has resulted in the production of low-quality, non-recyclable clothing that worsens the depletion of natural resources. Economically, the industry faces potential decline due to shortages of raw materials, rising costs for energy, water, and labor, and disruptions from events like the COVID-19 pandemic, which have notably affected French fashion retailers, leading some to bankruptcy or legal reorganization. Socially, recent incidents such as Rana Plaza and forced labor in cotton production have demonstrated severe ethical issues in the supply chain, highlighting the industry's failure to keep up with international human rights standards, including providing a living wage (International labor organization, 2023). Digital Product Passports in the textile sector within the EU's sustainable and circular textiles strategy could be a crucial tool for driving sustainable practices and innovation in the textile industry (European Parliamentary Research Service, 2024).

## 2.6 DPP timelines in accordance with the Circular Economy Action Plan

Digital Product Passports (DPPs) were initially brought into discussion in 2014 by the European Resource Efficiency Platform, primarily focusing on material recycling in the manufacturing process (Götz, 2022). The subsequent surge in attention towards circular economy and product sustainability within legislative discussions underscored the significance of DPPs, particularly highlighted by the European Green Deal and the circular economy in 2019. As an integral part of the proposed Ecodesign for Sustainable Products Regulation and a key action under the Circular Economy Action Plan (CEAP), DPPs are expected to set the foundation for the gradual introduction of a digital product passport in at least three key markets by 2024 (European Commission, 2022). The EC specified eight priority industries (i.e., electronics, vehicles, textiles, plastics, construction and buildings, furniture, and chemicals) (European Commission, no date). In total, delegated acts for 13+ product groups are expected to be drafted by 2030, with a draft for batteries already existing and coming into force in 2027.

Representing an innovative approach for regulating circularity, DPPs present unresolved challenges in scope, technology, and data (Wbcsd, 2023). Despite being tailored to specific product groups by the European Commission, their adoption across sectors faces potential delays due to these challenges. By severing the link between economic growth and material extraction, waste, and carbon emissions, early DPP-enabled transparency and swift implementation can have a significant global impact. While the eventual application of DPPs to at least 30 product categories is planned, their phased introduction begins with batteries, particularly industrial and electric car batteries, serving as the initial test case. As evidenced by the first proof of concept presented at the Davos Economic Forum this year, industrial organizations are taking proactive measures (Inriver, 2023; Umicore, 2023).

The complex process of creating and implementing digital product passports requires cooperation between several stakeholders, including manufacturers, consumers, and authorities. As such, the project timeline is subject to change in response to various circumstances, as the European Commission's high-level timeline (Wbcsd-1, 2023) outlined.

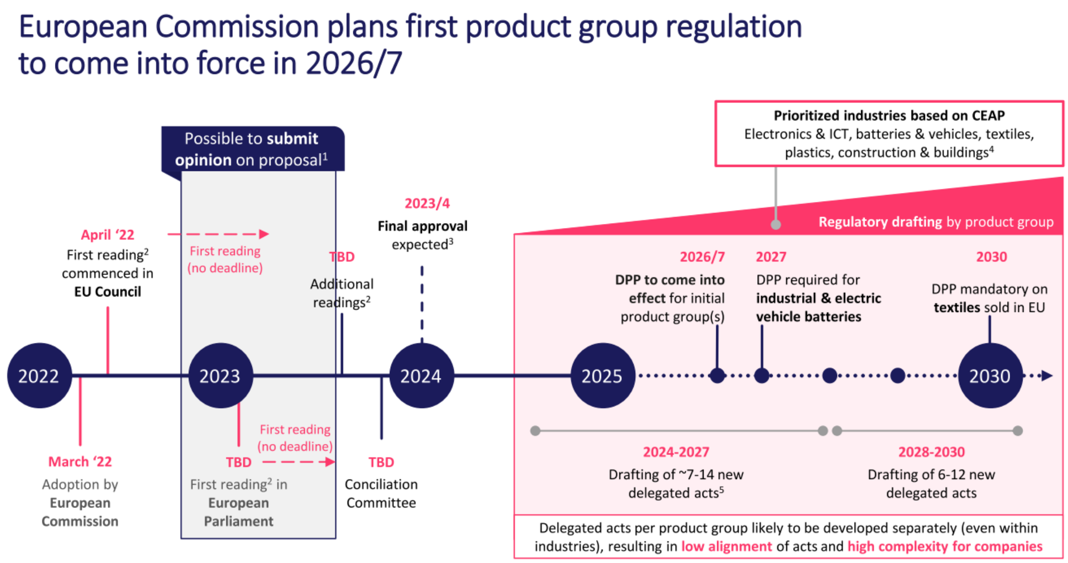


**Figure 2-2** Timeline for the DPP Implementation (Wbcsd1, 2023)

### 2.7 Concluding the Literature Review

In summary, this thorough literature review on Digital Product Passports (DPPs) shows that DPPs are a revolutionary way to improve circular economy practices and accomplish sustainable development objectives. By providing a detailed and accessible digital record of a product's entire lifecycle, DPPs facilitate greater transparency, resource efficiency, and sustainability in various industries. Throughout this review, we have explored the various capacities of DPPs in operating environmental sustainability and regulatory compliance, while also highlighting the challenges associated with their implementation. These challenges include the need for standardized definitions, complex data integration, and maintaining a balance between data privacy and transparency. The review also highlighted the importance of technological adaptability, financial investment, and reliable regulatory frameworks to fully realize the benefits of DPPs. The potential of DPPs to revolutionize product lifecycle management and support the transition to a more sustainable and circular global economy is significant. By enabling detailed tracking of resource use and waste reduction, DPPs empower consumers, manufacturers, and policymakers to make more informed decisions that support environmental sustainability. Moreover, as DPPs become more integrated into global standards, they are likely to influence future product design, use, and recycling practices across industries, fostering a resilient circular economy that benefits all stakeholders.

In conclusion, the ongoing development and improvement of DPP frameworks and their broader adoption are crucial for achieving global sustainability objectives. As industries and regulatory bodies continue to navigate the complexities of implementing these systems, the continued evolution of DPPs will play an important role in shaping a sustainable, transparent, and efficient future. The collaboration among all parties involved—enhanced by the digital capabilities of DPPs—will be essential in overcoming the existing challenges and unlocking the full potential of this innovative technology.

## 3. Methods and Material

The methodology section of this thesis begins with a detailed explanation of the research design and approach undertaken to investigate the barriers to the successful implementation of Digital Product Passports (DPPs), focusing on their interrelationships and the strategies to overcome them. The key to this exploration is the use of Interpretive Structural Modeling (ISM) combined with the Delphi Technique, a methodological combination aimed at leveraging expert insights and systematically analyzing the complexities of implementation barriers.

This methodical approach clarified the structural relationships between different implementation barriers of Digital Product Passports, as outlined by Warfield (Warfield, 1974) and further developed by Attri, Dev, and Sharma (Attri, Dev and Sharma, 2013). The power of this methodology lies in its capacity to convert unstructured qualitative assessments into a visual model that is structured and maps out the relationships and hierarchy between various elements, in this case, the obstacles to the implementation of DPP. Serving as a powerful tool for analysis, ISM assists in understanding the complex network of dependencies and influences within a system.
The construction of the (Interpretive Structural Modeling) model involves several key steps based on the ranked barriers and their interrelations already identified (Ebrahimi, Khajeheian, *et al.*, 2023) ;

1- Identifying components that are relevant to the issue or problem—a survey may be used for this.
2- Defining a contextual relationship between the elements that will guide the examination of element pairs.
3- Creating a structural self-interaction matrix (SSIM) of the system's elements, which shows the relationships between them in pairs.
4- Developing a reachability matrix from the SSIM, and examining the matrix for transitivity – transitivity of the contextual relation is a fundamental assumption in ISM which states that if element A is related to B and B is related to C, then A is related to C.
5- Dividing the reachability matrix into different levels.

6- Build a directed graph (digraph) based on the relationships listed above in the reachability matrix, then eliminate the transitive links.
7- Setting the statements in place of element nodes in the resulting digraph to create an ISM-based model.
8- Examining the model for conceptual consistency and making the required adjustments.

### 3.1 Data Collection and Delphi Technique

The Delphi method, developed in the 1950s by Dalkey and Helmer at the Rand Corporation (Dalkey Norman and Helmer Olaf, 1963), is a systematic way to gather and arrange expert opinions on particular subjects (Sobaih, Ritchie and Jones, 2012), regardless of the associated practicalities and limitations such as time and geographical logistics, which may have an influence.

Employing the Delphi technique also enhances the research with a broad and in-depth array of insights. This method underpins our methodology, ensuring that the conclusions are backed by a significant consensus among esteemed professionals in sustainability and business. Thanks to the iterative nature of the process and the careful selection of knowledgeable experts, the study is poised to significantly advance the understanding of challenges in the successful implementation of digital product passports.

The procedure started with a systematic process to identify experts for the study, focusing on individuals with the requisite knowledge and experience. The criteria for expertise required candidates to have at least ten years of study or work experience in the fields of sustainability, circular economy, and digital innovation. Experts were identified through professional networks such as LinkedIn. Invitations outlining the study's objectives were sent to selected individuals. After receiving the participants' acceptance, a panel of 10 experts from diverse fields related to sustainability, circular economy, and digital innovation was finally assembled. To determine the reliability of the measuring instrument, the ICC coefficient value was confirmed in terms of compatibility. This panel was employed to use the Delphi method for gathering opinions and judgments on the barriers identified in the literature review.

The process started with the distribution of a detailed document via email, introducing the identified barriers based on the literature review to the panel of experts, ensuring their familiarity with the analysis scope. This step was followed by the first Delphi round, titled "Exploration and Insight Gathering," where experts were invited to reflect on these barriers and offer insights from their expertise. They were encouraged to provide additional comments, highlight any overlooked aspects, or reaffirm the significance of the barriers, aiming for a comprehensive understanding and consensus on each barrier's implications and relevance (Naisola-Ruiter, 2022).

Finally, with the consultation of the group, nine factors were determined. A list of nine constructs was identified, as shown in Table 1.

**Table 1.** Identified factors based on experts' ideas and literature review (Own work)

| Number | Factors | Key References |
|---|---|---|
| F1 | Data Privacy and Confidentiality | (Götz, 2022)<br>(Jansen *et al.*, 2023)<br>(Psarommatis and May, 2024)<br>(Adisorn, Tholen and Götz, 2021)<br>(Walden, Steinbrecher and Marinkovic, 2021)<br>(TANNER AG, 2021)<br>(European Commission Green Public Procurement, no date)<br>(Durand *et al.*, 2022) |
| F2 | Intellectual Property Rights (IPR) Protection | (Götz, 2022)<br>(Walden, Steinbrecher and Marinkovic, 2021)<br>(European Commission, 2020a)<br>(Böckel et l.,2021)<br>(Munaro and Tavares, 2021)<br>(Jansen *et al.*, 2023) |
| F3 | Technical Implementation and Infrastructure | (Götz, 2022)<br>(van Capelleveen *et al.*, 2023) |

| | | |
|---|---|---|
| | | (Adisorn, Tholen and Götz, 2021)<br>(Honic *et al.*, 2021) (Ye *et al.*, 2020)<br>(Munaro and Tavares, 2021)<br>(Anastasiades et al., 2021)<br>(European Commission, 2020b)<br>(Chahine, 2021)<br>(Der Informationsdienst des Instituts der deutschen Wirtschaft, 2021)<br>(Durand *et al.*, 2022)<br>(Michele Galatola, 2022)<br>(Donetskaya and Gatchin, 2021)<br>(Guth-Orlowski, 2021) |
| F4 | Stakeholder Engagement and Collaboration | (Götz, 2022)<br>(Sepasgozar et al., 2020)<br>(Bouwend Nederland, 2022)<br>(Zhang *et al.*, 2021)<br>(Jansen *et al.*, 2023)<br>(Adisorn, Tholen and Götz, 2021) |
| F5 | Education and Awareness | (Götz, 2022)<br>(Sepasgozar et al., 2020)<br>(Bouwend Nederland, 2022) |
| F6 | Regulatory Compliance and Standards Adherence | (Götz, 2022)<br>(Böckel, Nuzum and Weissbrod, 2021; Holla, 2021)<br>(Munaro et al., 2019)<br>(Munaro and Tavares, 2021)<br>(Michele Galatola, 2022)<br>(Durand *et al.*, 2022)<br>(Plociennik *et al.*, 2022) |
| F7 | Resource Allocation and Investment (Upfront Capital and Operating Expenses, Data Registration Costs) | (Götz, 2022)<br>(Jansen *et al.*, 2023)<br>(Adisorn, Tholen and Götz, 2021)<br>(Psarommatis and May, 2024)<br>(Böckel, Nuzum and Weissbrod, 2021)<br>(Munaro and Tavares, 2021)<br>(Adisorn, Tholen and Götz, 2021) |
| F8 | Interoperability and Data Exchange | (Götz, 2022) |

| | | |
|---|---|---|
| | | (van Capelleveen *et al.*, 2023)<br>(Durand *et al.*, 2022)<br>(Koppelaar *et al.*, 2023)<br>(Psarommatis and May, 2024)<br>(Jansen *et al.*, 2023) |

**3.2. Building adjacency matrix or Structural self-interaction matrix (SSIM)**

The experts' evaluations of the pairwise interactions between barriers were represented in this matrix, which used a standard notation scheme to indicate the influence's direction. Since it offers the raw data needed to model the system's structure, the SSIM serves as a foundation for the ensuing analytical stages.

In SSIM, each element is compared with every other element to assess the nature of their relationship. This assessment typically uses a set of predefined codes to indicate the direction and type of influence between pairs of elements:

V indicates that element F1 influences element F2.
A signifies that element F2 influences element F1.
X represents a bidirectional influence, meaning both elements influence each other.
O means no direct influence between the elements.

The SSIM process involves expert judgments or data analysis to fill out the matrix according to these codes. This matrix is crucial for the next steps in the ISM process, such as the development of an Adjacency Matrix, a reachability matrix, and, eventually, the construction of a hierarchical model that visually represents the relationships and levels of influence among all the elements. SSIM thus provides a structured way to capture and interpret complex interdependencies, facilitating deeper insights into the system's structure and dynamics.

The contextual relationships among nine factors are constructed in an Adjacency Matrix based on the feedback from 10 experts (Table 2). Most direct-effect relationships were found between F6

(Regulatory environment) and other factors. The least direct-effect relationships were between F5(Resource control), F8(Technical features), and other factors.

**Table 2**. Structural self-interaction matrix (SSIM) – (Own work)

| | F8 | F7 | F6 | F5 | F4 | F3 | F2 | F1 |
|---|---|---|---|---|---|---|---|---|
| F1 | V | V | V | V | V | V | V | |
| F2 | V | O | O | O | X | V | | |
| F3 | V | O | V | O | V | | | |
| F4 | O | X | O | O | | | | |
| F5 | O | O | X | | | | | |
| F6 | V | O | | | | | | |
| F7 | O | | | | | | | |
| F8 | | | | | | | | |

**3.3. Initial Reachability Matrix (IRM)**

This step involves replacing V, A, X, and O in the SSIM with 1 or 0, depending on the position, to create a binary matrix known as the initial reachability matrix (Table 3).

According to several authors (Azevedo *et al.*, 2019; Ebrahimi, Khajeheian, *et al.*, 2023) the conversion follows a set of rules:

- If the (i, j) entry in the SSIM is V then the (i, j) entry in the initial reachability matrix becomes 1 and the (j, i) entry becomes 0.

- If the (i, j) entry in the SSIM is A, then the (i, j) entry in the initial reachability matrix becomes 0 and the (j, i) entry becomes 1.

- If the (i, j) entry in the SSIM is X then the (i, j) entry in the initial reachability matrix becomes 1 and the (j, i) entry becomes 1.

- If the (i, j) entry in the SSIM is O, then the (i, j) entry in the initial reachability matrix becomes 0 and the (j, i) entry also becomes 0.

**Table 3** Initial Reachability Matrix (IRM) – (Own work)

| | F1 | F2 | F3 | F4 | F5 | F6 | F7 | F8 |
|---|---|---|---|---|---|---|---|---|
| F1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| F2 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 |
| F3 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 |
| F4 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| F5 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| F6 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| F7 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| F8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

### 3.4. Developing reachability matrix to final reachability matrix (IRM)

The Final Reachability Matrix (FRM) is derived from the Initial Reachability Matrix (IRM), including both the direct relationships initially identified and the relationships determined through the principle of transitivity. The development of the FRM from the IRM involves a methodical process that begins with power iteration analysis—a computational technique performed using MATLAB, a high-performance technical computing language well-suited for matrix operations. Power iteration was used to identify dominant eigenvalues and their corresponding eigenvectors, a step crucial for various analytical processes, including those applied to the reachability matrix within the Interpretive Structural Modeling (ISM) framework. Transitivity, a fundamental concept in ISM, suggests that if element A influences element B, and element B in turn influences element C, then an indirect influence of A on C is established(Warfield, 1974). This concept is systematically applied in the transition from the IRM to the FRM to identify and clarify indirect influences among elements. As a result, the FRM serves as a thorough map of all direct and indirect interactions inside a system, giving rise to complex interactions and contributing to the development of strategic decisions.

After the application of the transitivity principle, the final Reachability matrix was obtained (Table 4). For every variable, the reachability and predecessor sets can be found using the final reachability matrix. Each variable's driving force is equal to the total number of variables it can affect, including itself. A variable's dependence is determined by all the variables (including itself) that could have an impact on it. The MICMAC analysis or cross-impact analysis below makes use of these motivating factors and dependencies (Ebrahimi et al., 2023b). Cells that have applied transitivity are indicated by entries that are marked with a "1*". This indicates that even in cases when two factors do not directly relate to one another, an indirect relationship may exist as a result of a series of other elements.

$$R_f = R_j^K = R_j^{K+1}, K > 1$$

where $R_f$ is the FRM, and $R_i$ is the IRM

**Table 4** Final Reachability Matrix (IRM) – ( Own work)

| | F1 | F2 | F3 | F4 | F5 | F6 | F7 | F8 | Driving power |
|---|---|---|---|---|---|---|---|---|---|
| F1 | 1* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 8 |
| F2 | 0 | 1* | 1 | 1 | 1* | 1* | 1* | 1 | 7 |
| F3 | 0 | 1* | 1* | 1 | 1* | 1 | 1* | 1 | 7 |
| F4 | 0 | 1 | 1* | 1* | 1* | 1* | 1 | 1* | 7 |
| F5 | 0 | 0 | 0 | 0 | 1* | 1 | 0 | 1* | 3 |
| F6 | 0 | 0 | 0 | 0 | 1 | 1* | 0 | 1 | 3 |
| F7 | 0 | 1* | 1* | 1 | 1* | 1* | 1* | 1* | 7 |
| F8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1* | 1 |
| Dependence power | 1 | 5 | 5 | 5 | 7 | 7 | 5 | 8 | |

Note: "*" represents the values that are changed from "0" to "1" and displayed with 1*, power=k=4, during the transitivity check.

### 3.5. Level partitions

In the Interpretive Structural Modeling (ISM) methodology, level partitions refer to the process of structuring and analyzing complex systems by identifying and organizing elements based on their relationships. The methodology aims to create a hierarchical structure (or model) that illustrates how elements are interrelated within a system.

During the ISM process, the reachability matrix is used to identify the relationships between elements. The matrix is analyzed to determine which elements influence others. Based on this analysis, elements are partitioned into different levels. This involves:

- Determining the reachability set for each element (the set of elements that can be reached from a given element)
- Establishing the antecedent set for each element (the set of elements that can reach a given element)
- Identifying the intersection of these sets for each element

The elements for which the reachability and the intersection sets are the same occupy the top level in the ISM hierarchy. The top-level element in the hierarchy would not help achieve any other element above its level (Singh and Kant, 2008). Once the top-level element is identified (Table 5), it is separated from the other elements. Then, the same process is repeated to find out the elements in the next level. This process is continued until the level of each element is found (Table 8). The tables show four levels for the ISM model. F8 (Interoperability and Data Exchange) is a top-level element in the ISM model of this research.

**Table 5**. Level partitioning factors (first iteration) – (Own work)

| Factors | Reachability set | Antecedent set | Intersection set | Level |
|---|---|---|---|---|
| F1 | 1,2,3,4,5,6,7,8 | 1 | 1 | |
| F2 | 2,3,4,5,6,7,8 | 1,2,3,4,7 | 2,3,4,7 | |
| F3 | 2,3,4,5,6,7,8 | 1,2,3,4,7 | 2,3,4,7 | |
| F4 | 2,3,4,5,6,7,8 | 1,2,3,4,7 | 2,3,4,7 | |
| F5 | 5,6,8 | 1,2,3,4,5,6,7 | 5,6 | |
| F6 | 5,6,8 | 1,2,3,4,5,6,7 | 5,6 | |
| F7 | 2,3,4,5,6,7,8 | 1,2,3,4,7 | 2,3,4,7 | |
| F8 | 8 | 1,2,3,4,5,6,7,8 | 8 | 1 |

This table presents the process of level partitioning in an Interpretive Structural Modeling (ISM) methodology during the first iteration. It details factors (F1 to F8), along with their respective reachability, antecedent, and intersection sets. The purpose is to organize these factors into levels based on their influence within the system. Here's the interpretation of each column and the final determination of the level for each factor:

- Factors (F1 to F8): These are the elements or variables being analyzed in the system.
- Reachability Set: This indicates which factors can be reached from a given factor. For example, F1 can reach all factors (1 through 8), suggesting it has a broad influence.
- Antecedent Set: This set contains factors that can reach the given factor. F8, for example, is influenced by all other factors (1 through 8), showing it's a consequence of many inputs.
- Intersection Set: The intersection of the reachability and antecedent sets for each factor. It identifies which factors are both reached by and can reach the given factor.
- Level: This is determined based on the intersection set. A factor is assigned a level when its reachability and antecedent sets match its intersection set, indicating no higher-level factors influence it.

This section provides a detailed analysis of the findings presented in **Table 5**, outlining the implications and insights derived from the data:

F8 (Interoperability and Data Exchange) is a top-level element in the ISM model of this research. It is the only factor with its reachability set matching its intersection set, making it a top-level factor (Level 1). It is influenced by all factors but does not influence any. F1 has an antecedent set of just itself, indicating it's a foundational factor.

Once the top-level element is identified (Table 5), it is separated from the other elements. Then, the same process is repeated to find out the elements in the next level.

**Table 6**. Level partitioning factors (second iteration) - (Own work)

| Factors | Reachability set | Antecedent set | Intersection set | Level |
|---|---|---|---|---|
| F1 | 1,2,3,4,5,6,7 | 1 | 1 | |

| | | | | |
|---|---|---|---|---|
| F2 | 2,3,4,5,6,7 | 1,2,3,4,7 | 2,3,4,7 | |
| F3 | 2,3,4,5,6,7 | 1,2,3,4,7 | 2,3,4,7 | |
| F4 | 2,3,4,5,6,7 | 1,2,3,4,7 | 2,3,4,7 | |
| F5 | 5,6 | 1,2,3,4,5,6,7 | 5,6 | 2 |
| F6 | 5,6 | 1,2,3,4,5,6,7 | 5,6 | 2 |
| F7 | 2,3,4,5,6,7 | 1,2,3,4,7 | 2,3,4,7 | |

In the second iteration of the level partitioning (Table 6) for the ISM process, it is observed F1 stands out because its reachability set matches its antecedent set precisely, placing it obviously at the initial level of the hierarchy. This suggests F1 is influencing other factors without being influenced by them in this iteration, thus assigned to Level 1. F5 and F6 are assigned to Level 2, as indicated by their intersection sets matching their antecedent sets and having a unique reachability that doesn't extend beyond themselves and each other. This positioning indicates they are influenced by factors including themselves and potentially influence each other but do not extend their influence beyond this scope within the current model structure.

This iteration effectively differentiates the roles of the factors within the system, distinguishing between foundational elements (F1), those that operate within a more confined scope (F5 and F6), and others that play a more complex, interconnected role (F2, F3, F4, and F7). Further iterations would continue to refine these levels, aiming to achieve a fully stratified model that accurately reflects the system's structure.

**Table 7**. Level partitioning factors (third iteration) – (Own work)

| Factors | Reachability set | Antecedent set | Intersection set | Level |
|---|---|---|---|---|
| F1 | 1,2,3,4, 7 | 1 | 1 | |
| F2 | 2,3,4,7 | 1,2,3,4,7 | 2,3,4,7 | 3 |
| F3 | 2,3,4,7 | 1,2,3,4,7 | 2,3,4,7 | 3 |
| F4 | 2,3,4,7 | 1,2,3,4,7 | 2,3,4,7 | 3 |
| F7 | 2,3,4,7 | 1,2,3,4,7 | 2,3,4,7 | 3 |

This third iteration (Table 8) F2, F3, F4, and F7 are grouped together at Level 3. This grouping is determined by their intersection sets matching their antecedent sets, showing that these factors are mutually significant and interdependent. Their reachability sets include one another, indicating a closely knit web of influence amongst them without extending beyond this group.

**Table 8**. Level partitioning factors (fourth iteration) – (Own work)

| Factors | Reachability set | Antecedent set | Intersection set | Level |
|---|---|---|---|---|
| F1 | 1 | 1 | 1 | 4 |

In the last iteration of the level partitioning, F1 is shown now isolated with its reachability set, antecedent set, and intersection set all reduced to just itself. This indicates that F1 is completely independent, influencing only itself and not being influenced by any other factors within the system. As a result, F1 is assigned to Level 4.

### 3.6. ISM model and MICMAC analysis

Following the level partitioning results, the diagram of the final ISM model was created and is displayed in Figure 1. Reviewing tables 5 to 8, it could be seen that "Interoperability and Data Exchange" occupies Level I, positioning it at the top of the ISM model. Figure 1 outlines the research variables, their interconnections, and the hierarchical level assigned to each variable. Significantly, Figure 1 illustrates that "Data Privacy and Confidentiality" forms the foundation of our framework. The strategic placement of this variable indicates its role as a foundational element that influences the performance of other factors within our study, pointing out that it is crucial for achieving higher-level goals such as interoperability, which ultimately leads to the adoption of digital product passports.

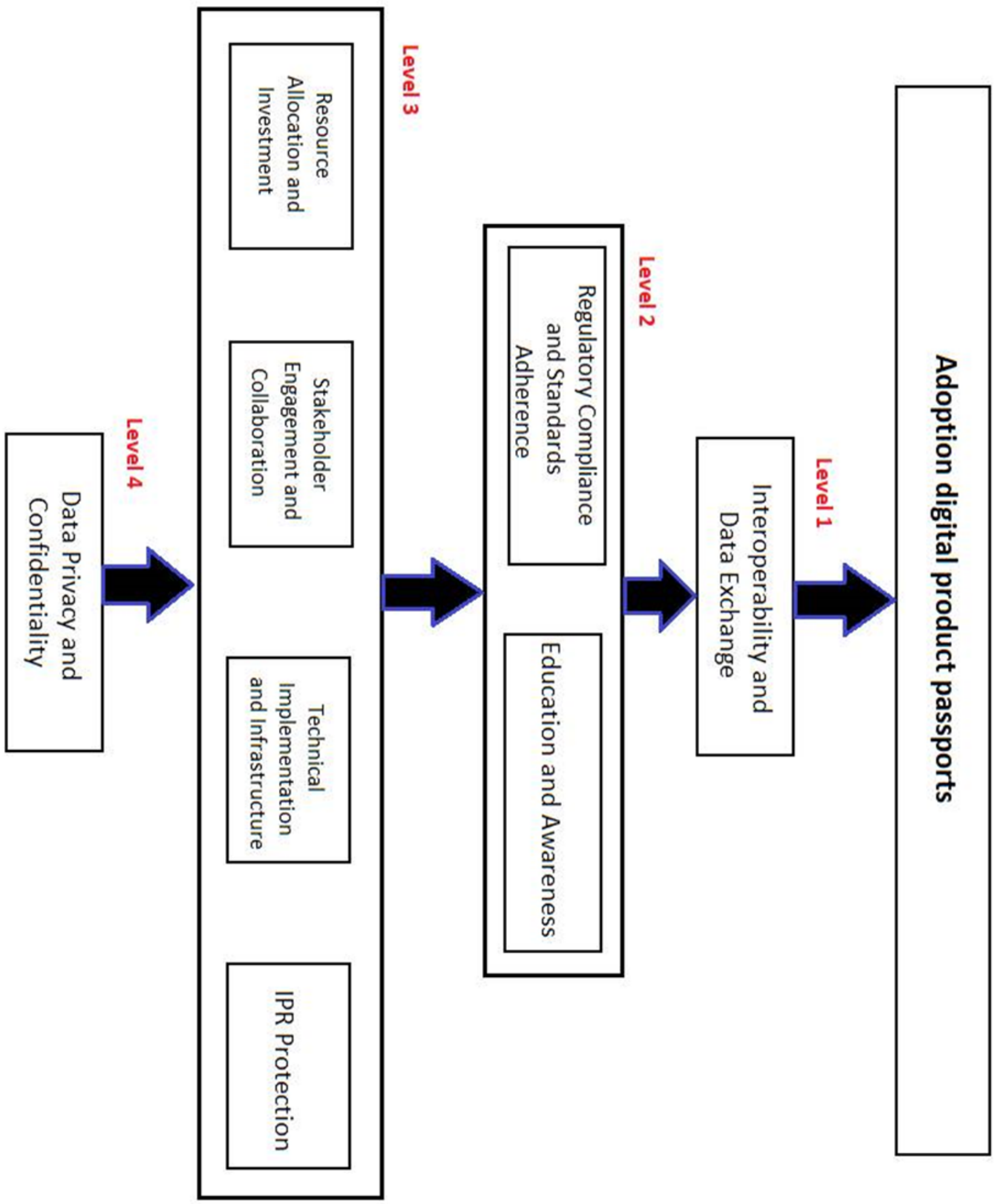


**Fig 3-1**. ISM model – (Own wok)

To further analyze how these outcomes are distributed and navigate the complex reaction loops and development paths of hierarchies within the element set, the Matrices d'Impacts Croisés Multiplication Appliquée à un Classement (MICMAC) method is deployed. By analyzing the network of influences and dependencies that define our study's structure and results, this analytical technique enhances the ISM model(T.S and Ravi, 2023). MICMAC analysis or Cross-Impact Matrix Multiplication is a strategic tool used in future studies and systems analysis. Developed by Michel Godet, the analysis is part of the field of strategic foresight and planning, helping organizations and researchers to understand the complex interactions and dynamics within a system (Godet and Michel, 1994). The purpose of MICMAC analysis is to determine the degree of mutual dependency and the ways in which different components within a system influence each other. This procedure assists in prioritizing strategic actions and draws attention to the important drivers inside the system, which improves decision-makers' capacity to allocate resources efficiently. The examination contributes to predicting future possibilities by providing a more detailed view of the system's structure through an understanding of the direct and indirect interdependencies between elements. Strategic planning and well-informed decision-making depend on this comprehensive point of view (Krishnan *et al.*, 2021; Ebrahimi, Dustmohammadloo, *et al.*, 2023).

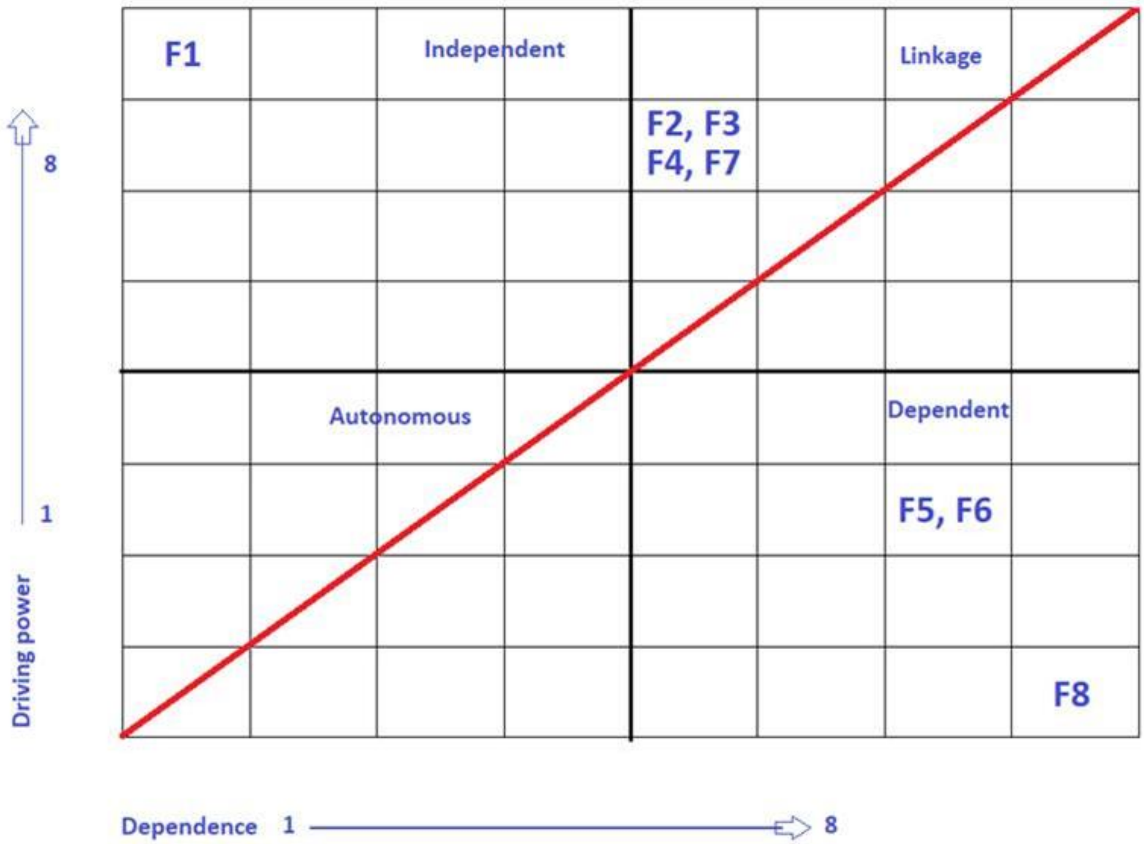


**Fig 3-2**. MICMAC analysis – (Own work)

## 4. Result / Discussion

This research employed a unique combination of the Delphi Technique and Interpretive Structural Modeling (ISM), which provided an effective structure for analyzing the complex network of barriers to Digital Product Passport implementation. Based on the agreement of experts, the Delphi Technique added new perspectives to the analysis of well-known individuals in digital innovation, sustainability, and the circular economy. Meanwhile, ISM facilitated a structured exploration of the complex interactions among identified barriers, illustrated in a multi-level hierarchical model. This dual-methodological approach allowed for an in-depth understanding of how various factors influence one another within a systemic context, which is critical for developing effective strategies for DPP integration. The visual representation of these relationships in Figure 3-1 further clarified the hierarchy of barriers from foundational to peripheral, emphasizing their interrelationships essential for comprehensive policy and organizational strategies.

Based on a wide range of academic publications and enhanced by the opinions of experts experienced in digital innovation, sustainability, and the circular economy, the study identified 8 main constraints to the adoption of DPPs (Table 1). These results highlight the complex relationships between variables that must be managed to promote the implementation of DPPs. These identified barriers, which represent major challenges in the integration of DPPs within current systems, were then subjected to a detailed structuring process using the ISM and MICMAC methodologies.

The ISM model, intricately illustrated in Figure 3-1, offers a structured analysis of the key factors influencing the implementation of Digital Product Passports (DPPs), organized into four distinct levels. Each level represents a different degree of impact on the system, with a clear delineation of the contextual links that interconnect each variable within these levels. This model not only aids in visualizing the hierarchy of constraints but also in understanding how each layer supports the other in the complex system of digital product management. At the very foundation of this hierarchy, positioned at Level 1 as shown in Figure 3-1 and detailed in Table 3-5, is "Interoperability and Data Exchange." This factor is critical as it supports the entire operational success of DPPs, enabling seamless communication and data flow across different platforms and stakeholders. Its placement at the top of the hierarchy highlights its fundamental role in ensuring that all system components can interact without barriers, which is essential for the effective functioning of DPPs. Ascending to Level 2, as elaborated in Figure 3-1 and Table 3-6, are the factors "Regulatory Compliance and Standards Adherence" along with "Education and Awareness." These elements are vital for supporting the primary goal established by the first level. Regulatory compliance ensures that all operations align with legal standards and industry regulations, which is crucial for maintaining system integrity and trust. At the same time, education and awareness initiatives are imperative for fostering an understanding of the DPPs' benefits and operational procedures, thereby enhancing stakeholder engagement and facilitating smoother adoption processes. Level 3, as extracted from Table 3-7, includes "Resource Allocation and Investment," "Stakeholder Engagement and Collaboration," "Technical Implementation and Infrastructure," and "Intellectual Property Rights (IPR) Protection." This level demonstrates the need for substantial resource investment and strategic collaboration among various stakeholders. Effective resource allocation ensures that sufficient funds, technology, and human capital are available to support DPP initiatives. Meanwhile, reliable technical infrastructure sets the groundwork for advanced functionalities, and IPR protection safeguards the proprietary technologies and data essential for maintaining competitive advantages and ensuring privacy. Finally, Level 4, which forms the foundation of the system and is detailed in Table 3-8, includes "Data Privacy and Confidentiality." This level is critical as it deals with the protection of sensitive information, a foundational requirement for any system dealing with data exchanges. Ensuring data privacy and confidentiality not only builds trust among users but also complies with stringent regulatory requirements that govern data handling and security. The ISM model thus provides a complex and dynamic representation of how these components, though varied in their functions and impacts, are interdependent and collectively essential for the successful integration of Digital Product Passports. Each level's distinct but complementary roles highlight the complexity of managing digital identities and data in a way that is both efficient and secure, reflecting the sophisticated nature of modern digital systems. The strategic organization of these factors into levels helps clarify the pathways through which improvements in lower levels can significantly enhance the functionality and reliability of the entire system, thereby promoting broader interoperability and smoother operation across the DPP framework.

The research proceeded in addition to the first hierarchy by using MICMAC analysis to investigate the strategic placement of factors along a range of driving power and dependence.  In the analysis illustrated in Figure 3-2, factors within a system are categorized into four segments based on their driving and dependence powers: autonomous, dependent, linkage, and driving. Each variable in these categories has a distinctive cause and effect based on where it falls within the category. The red diagonal line represents the strategic importance limit, indicating that factors aligned with this line, such as "(IPR) Protection", "Technical Implementation and Infrastructure", " Stakeholder Engagement and Collaboration ", and " Resource Allocation and Investment ", are considered strategic due to their balanced driving and dependence powers. They are the most strategic factors to achieve research goals. Due to its great influence and minimum dependence, "Data Privacy and Confidentiality" is categorized as a driving factor, indicating that it is the main force behind change. The linking factors "(IPR) Protection", "Technical Implementation and Infrastructure", " Stakeholder Engagement and Collaboration ", and " Resource Allocation and Investment " are identified as being important for system coherence, having a considerable influence, and being responsive to manipulation. Their double function in the system as influencers and responders aligns with earlier studies on system dynamics and the role linking factors play in a system's stability and flexibility. "Education and Awareness" and "Regulatory Compliance and Standards Adherence" are labeled as dependent, and highly influenced by other factors but with minimal influence themselves. "Interoperability and Data Exchange" is notable for its low driving power and excessive reliance. The absence of factors in the 'Autonomous' category suggests that all identified elements are in some way integrated into the system's dynamics.

The practical utilization of the Delphi Technique and Interpretive Structural Modeling (ISM) approaches in diverse fields, such as sustainability, illustrates their relevance in complex problem-solving situations. According to Ahmad and Qahmash (Ahmad and Qahmash, 2021), the ISM process aids in converting unstructured information into organized, practical insight, which is especially helpful in multidisciplinary subjects like sustainability. The importance of "Interoperability and Data Exchange" and other identified constraints, as well as the results of this research, highlight the necessity of strategic solutions. The importance of "Interoperability and Data Exchange" and other identified constraints, as well as the results of this research, highlight the necessity of strategic interventions. It has been demonstrated that strategic elements like "IPR Protection" and "Technical Implementation and Infrastructure" are essential to attaining system coherence, and the literature further supports their significance by arguing that stability and adaptability within systems are largely dependent on an understanding of interdependencies (Attri, Dev and Sharma, 2013).

Including the timeline from Figure 2-2 in the results section, we can discuss the legislative context in which the identified barriers to Digital Product Passports must be addressed. The image details a regulatory roadmap, from the initial adoption of legislation by the European Commission in March 2022 to the expected enforcement of Digital Product Passports in various industries by 2026/7. The progression of this legislation, through the various stages of the EU Council, Parliament, and anticipated final approvals, sets a framework within which the DPP must operate. The prioritization of industries based on the Circular Economy Action Plan (CEAP)—such as electronics, batteries, textiles, and construction—adds further layers to the strategic factors identified in the ISM and MICMAC analyses. These analyses revealed that "Interoperability and Data Exchange" is a vital concern at the top level, underpinning the operation of DPPs. Regulatory compliance and education are also key, supporting the adoption of DPPs, which aligns with the legislative focus of the EU's timeline. Furthermore, "Technical Implementation and Infrastructure" and "IPR Protection" are strategic factors for system coherence, aligning with the regulatory drafting and the development of new authorized acts anticipated between 2024-2027. This suggests that tackling such obstacles is not only a technical and operational challenge but also a strategic necessity given the legislative path.

## 5. Conclusions and Recommendations

This research, by strategically integrating the Delphi Technique with Interpretive Structural Modeling (ISM), has systematically identified the critical barriers that disrupt the implementation of Digital Product Passports (DPPs). This dual-methodological approach has not only identified but also organized these barriers into a comprehensive framework that aims to streamline the adoption process of DPPs across multiple sectors. As highlighted earlier, the eight key factors derived from this analysis provide crucial insights into the dynamics that influence the successful implementation of DPPs. These factors range from technical and infrastructural challenges to regulatory and market-driven considerations, each playing an important role in shaping the landscape in which DPPs operate.

Based on the results presented in detail in the previous section, maintaining data privacy and confidentiality emerges as the most significant independent barrier (level 4), highlighting the complex challenge of ensuring not all data within DPPs is publicly accessible. This necessitates strict regulations to manage data distribution effectively, balancing transparency with the protection of sensitive information. This issue has been underscored in several studies (Götz, 2022; Jansen et al., 2023; Psarommatis & May, 2024; Adisorn et al., 2021; Walden et al., 2021; TANNER AG, 2021), pointing out that transitioning to a transparent supply chain requires careful privacy consideration. To ensure data privacy and confidentiality in digital product passports, it is essential to consider various factors and technologies. By incorporating encryption and authentication mechanisms, as demonstrated in Tensor Network-Encrypted Physical Anti-counterfeiting Passports, data protection and privacy in digital passports can be further secured (Li *et al.*, 2021). Moreover, the utilization of blockchain technology has been suggested to provide privacy-preserving mechanisms that ensure data security and integrity (Rejeb *et al.*, 2023).

Protecting Intellectual Property Rights (IPR) within the framework of Digital Product Passports (DPPs) presents serious challenges. The requirement for producers to disclose data about their product components introduces potential issues related to IPR protection, stemming from the risk of revealing confidential information through data sharing. In order to guarantee the dependability and accessibility of shared info, it is necessary to address such concerns. These issues have been consistently highlighted in related research, including studies by (Böckel et l.,2021, Munaro & Tavares, 2021, Jansen et al., 2023). It is advised to take a multifaceted strategy to deal with the challenge of securing intellectual property rights (IPR) in digital product passports (DPPs). This includes implementing layered access controls to ensure data is only accessible to authorized users, applying data anonymization and encryption techniques to protect sensitive information, and integrating blockchain technology for secure and transparent data sharing. Proprietary data can be further protected by establishing precise legal frameworks, utilizing IPR markers inside DPPs, and allowing for the distribution of only non-sensitive information through selective data sharing. Establishing a safe and efficient DPP system also requires regular audits, commitment to industry standards, and promotion of best practices for data protection and IPR management.

The technical implementation and infrastructure required for Digital Product Passports (DPPs) present significant challenges and considerations for stakeholders. Implementing DPPs involves the development of a sophisticated digital framework capable of securely managing and sharing detailed product information throughout the product's lifecycle, from production to end-of-use. This requires an accurate and scalable infrastructure that can deal with vast amounts of data, ensure data integrity, and facilitate interoperability across diverse systems and stakeholders. According to the articles like van Capelleveen et al. (2023), Honic et al. (2021), Ye et al. (2020), Munaro & Tavares (2021), Anastasiades et al. (2021), Chahine (2021), Michele Galatola (2022), Donetskaya & Gatchin (2021), and Guth-Orlowski (2021), one of the primary technical challenges is the formation of a standardized data format that allows for seamless communication and data exchange among manufacturers, regulators, consumers, and recyclers. Standardization is crucial for ensuring that DPPs can be universally read and understood, regardless of the industry or geographic location. This involves not only agreeing on the types of data to be included but also on how this data is structured, stored, and accessed. Another significant issue is the need for secure data storage and transmission methods that protect sensitive information against unauthorized access and cyber threats. This may require implementing advanced encryption methods, and secure access controls. Moreover, the infrastructure must be scalable and adaptable to accommodate future technological advancements and changes in regulatory requirements. It should allow for the easy addition of new data types and facilitate updates to existing DPPs without compromising data integrity or security. Experts advise that addressing these technical implementation and infrastructure challenges for Digital Product Passports (DPPs) necessitates collaboration among industry leaders, technology experts, and policymakers. This collaboration should aim to develop clear standards, adopt best practices in data security, and invest in the advancement of technologies capable of supporting the complex needs of DPP systems.

Stakeholder engagement and collaboration are crucial for gaining support and facilitating the adoption of Digital Product Passports (DPPs) throughout the value chain. Research by Sepasgozar et al. (2020), Bouwend Nederland (2022), and Zhang et al. (2021) highlights the importance of involving businesses, policymakers, and even consumers in the process of identifying and addressing issues related to DPP's implementation. For DPPs to be successfully implemented, it is essential to engage stakeholders at every step, from raising awareness about DPPs' benefits to addressing any concerns and incorporating feedback to ensure the approach meets the diverse needs of all stakeholders. Fostering collaboration among these groups is vital to build consent, enhance transparency, and encourage collective action for the broad adoption of DPPs. This cooperative strategy is key to the success and long-term viability of DPP initiatives.

As the last strategic factor placed in level 3 based on the findings of this study, resource allocation, and investment are crucial considerations in the implementation of Digital Product Passports (DPPs) due to the substantial investments required in technology infrastructure. Implementing DPPs would require significant financial investments to acquire and deploy the requisite technology infrastructure. This may include investments in data management systems, cloud storage solutions, data analytics tools, and cybersecurity measures. Additionally, organizations may need to allocate resources toward hiring skilled personnel or training existing staff to manage and operate the DPP ecosystem effectively. However, the necessity for substantial resources can serve as a barrier for some businesses, particularly small and medium-sized enterprises (SMEs) with limited budgets and capacity. SMEs may face challenges in allocating the necessary financial resources and expertise to implement DPPs effectively, potentially hindering their adoption and participation in DPP initiatives. Addressing the challenge of resource allocation and investment for the implementation of Digital Product Passports (DPPs), especially in considering the substantial investments required in technology infrastructure and the upcoming EU regulations, necessitates a strategic approach that involves government support and guidance. The latest publications and studies like Götz 2022, Jansen et al. 2023, Adisorn et al. 2021, Psarommatis & May 2024, Böckel et al. 2021, and Munaro & Tavares 2021, suggest several recommendations for addressing these barriers, particularly for small and medium-sized enterprises (SMEs) which play a crucial role in the economy but may lack the necessary resources for such digital transformations. It is recommended that governments can offer financial assistance through subsidies and grants specifically aimed at supporting the adoption of sustainable technologies like DPPs. These financial incentives can help decrease the initial costs associated with acquiring the necessary technology infrastructure. Subsidies can be especially effective in offsetting the initial costs of installation, thereby making sustainable technologies more accessible. This is particularly beneficial for small and medium-sized enterprises (SMEs) with limited financial resources and in low-income countries where affordability is a major obstacle to adoption(De Groote and Verboven, 2019; Van de Ven *et al.*, 2022). Beyond financial support, governments can also facilitate technical assistance programs to help businesses, acquire the necessary expertise and skills for DPP implementation. This could include training programs, workshops, and access to consulting services focused on digital transformation strategies. The other solution can be establishing PPPs can provide a collaborative model where the technological and financial burden of implementing DPPs is shared between the government and private sector (Dunst *et al.*, 2019; Dzhikiya *et al.*, 2023). This can accelerate the adoption of DPPs by leveraging both public resources and private sector innovation. Offering tax incentives for businesses that invest in DPP technology and infrastructure can also lower the effective cost of these investments. Tax credits or deductions for expenses related to DPP implementation can make these initiatives more financially feasible for SMEs. Given the upcoming EU regulations that mandate the adoption of DPPs, these solutions not only align with the need to support businesses in complying with new standards but also emphasize the role of the government in facilitating this transition.

Moving on to the second-level factors, namely Education and Awareness and Regulatory Compliance and Standards Adherence, it is obvious that education is crucial in advancing the adoption and effective use of Digital Product Passports (DPPs) among both manufacturers and consumers. This involves educating stakeholders about the importance of DPPs, helping them understand the information provided, and encouraging sustainable decision-making based on that data. Manufacturers need insights into the benefits of DPPs, including their role in enhancing product lifecycle transparency, traceability, and sustainability. Manufacturers need to understand the value proposition of DPPs, including how they enhance transparency, traceability, and sustainability throughout the product lifecycle. Additionally, they require guidance on how to integrate DPPs into their operations and leverage the insights gained to optimize processes and enhance product offerings. They also need guidance on implementing DPPs into their operations and using their gained knowledge to improve processes and product offerings. Consumers, on the other hand, require education on the advantages of DPPs for making informed purchases, such as how they can find and understand information on product origins, environmental impacts, and disposal options(Adisorn, Tholen and Götz, 2021). Giving customers this information empowers them to make decisions about what to buy that are supportive of their sustainability beliefs, which in turn increases demand for clear, eco-friendly products. However, challenges such as bridging knowledge gaps, altering habits, and effectively transferring complex data to varied audiences may limit widespread education and awareness of DPPs. Research by Götz (2022), Sepasgozar et al. (2020), and Bouwend Nederland (2022) has brought attention to these issues. Thus, comprehensive educational initiatives, focused publicity campaigns, and collaborations with industry bodies and advocacy groups are essential in overcoming these obstacles and ensuring the successful implementation of DPPs.

Moreover, maintaining regulatory compliance necessitates planning for upcoming policies and activities in addition to following present laws and standards. Studies by Götz (2022), Böckel et al. (2021), Holla (2021), Munaro et al. (2019), Munaro & Tavares (2021), Michele Galatola (2022), Durand et al. (n.d.), and Plociennik et al. (2022) highlight how difficult it is to ensure compliance and how important it is for businesses to carefully and precisely navigate the regulatory environment. In order to properly comprehend the rules and guidelines regarding Digital Product Passports (DPPs) in their particular industry and geographical area, organizations must perform thorough assessments. This involves establishing the laws governing data security, privacy, environmental requirements, and product disclosure. Organizations must then create plans and procedures for incorporating these legal requirements into their DPP frameworks in order to achieve compliance. Implementing reliable data management protocols for meeting regulations such as the GDPR, establishing strict data security measures, and adopting standardized data formats for regulatory reporting are all critical steps in this process. Moreover, it is essential for organizations to stay informed about regulatory changes and anticipate future policy shifts that could affect DPP implementation. Adopting a proactive approach enables organizations to promptly modify their DPP strategies and maintain compliance with evolving regulatory requirements. Successfully navigating regulatory compliance for DPPs requires close collaboration with regulatory bodies, industry associations, and legal advisors. Through open communication and partnership, organizations can effectively go through the regulatory landscape, ensuring that their DPP initiatives are in full alignment with both current and upcoming regulatory standards and expectations.

Moving to the first-level factor identified in the ISM model, Interoperability and Data Exchange hold the most significance for the system's operation, presenting major obstacles in the Digital Product Passports (DPPs) implementation. These challenges require concerted efforts to ensure system compatibility across various sectors. Establishing common data-sharing standards and stakeholder coordination is crucial (Bellini and Bang, 2022). Interoperability involves the ability of DPP systems to smoothly exchange and make sense of data across different platforms and industries, requiring the adoption of uniform data formats, protocols, and interfaces to allow for effective communication and data exchange among disparate systems. This process expects collaborative efforts among stakeholders to set and adopt interoperability standards that meet the diverse needs of various sectors and participants. Götz (2022) and van Capelleveen et al. (2023) mentioned standardization, as a fundamental factor for achieving interoperability, which focuses on creating unified frameworks and protocols for data representation and exchange within DPPs. The goal is to align data structures, terminology, and methodologies, ensuring consistency and compatibility across systems and applications. This effort calls for cooperation among industry groups, regulatory authorities, and standards development organizations to craft and advocate for standards that are broadly accepted for DPP deployment. Addressing the complexities of interoperability and standardization requires dedicated collaboration and coordination among all stakeholders, including manufacturers, technology providers, industry associations, and regulatory bodies. This collective action is essential for defining interoperability prerequisites, developing technical specifications, and encouraging the adoption of standardized practices. Moreover, there's a continuous need to keep pace with emerging technologies and industry trends to maintain the relevance and flexibility of interoperability standards. By promoting collaboration and standardization, stakeholders can navigate interoperability challenges, leveraging DPPs to improve transparency, traceability, and sustainability throughout supply chains. Significant contributions to this field of study include works by, Durand et al. (n.d.), Koppelaar et al. (2023), Psarommatis & May (2024), Jansen et al. (2023), and DIN - DKE (n.d.).

In conclusion, the successful implementation of Digital Product Passports (DPPs) relies on overcoming identified barriers through strategic collaboration, regulatory alignment, technical innovation, and stakeholder engagement. By addressing these challenges, stakeholders can unlock the full potential of DPPs to enhance sustainability, traceability, and transparency throughout supply chains, aligning with the environmental and digital transformation goals of the European Union. Thus, DPPs can serve as a transformative tool that includes the product's journey from design to end-of-life management, ensuring a circular flow of information and resources. As illustrated in Figure 1, DPPs document the essence of a sustainable ecosystem by recording every phase of a product's existence, thoroughly detailing and accounting for it, and optimizing for environmental integrity and economic viability.

## 6. Summary

This thesis provides an in-depth exploration of the implementation barriers associated with Digital Product Passports (DPPs), set within the framework of the European Commission's Sustainable Product Regulation. The research is pivotal as it addresses the crucial elements required for enhancing product transparency, traceability, and sustainability throughout their lifecycle, which are fundamental to advancing the principles of the circular economy. By employing sophisticated research methodologies such as the Delphi Technique and Interpretive Structural Modeling (ISM), this study meticulously identifies and deciphers the complex interrelationships among various barriers that hinder the adoption of DPPs.

The thesis highlights eight major barriers: Data Privacy and Confidentiality, Intellectual Property Rights (IPR) Protection, Technical Implementation and Infrastructure, Stakeholder Engagement and Collaboration, Education and Awareness, Regulatory Compliance and Standards Adherence, Resource Allocation and Investment, and Interoperability and Data Exchange. It explores deeply into each barrier, with particular emphasis on 'Data Privacy and Confidentiality' as a foundational challenge. This barrier points to the delicate balance required between ensuring transparency and protecting sensitive information, a key concern in the broader context of data security and privacy laws. Similarly, 'Interoperability and Data Exchange' is highlighted as a critical upper-level challenge, essential for the seamless sharing of data across diverse platforms and industries which is instrumental for the operational success of DPPs.

The thesis offers a series of recommendations aimed at addressing these barriers, promoting the establishment of clear, reliable standards that could unify the diverse approaches across industries and borders. It suggests best practices in data security to safeguard sensitive information while maintaining the necessary level of transparency. Moreover, the study proposes enhanced collaborative efforts among industry leaders, technology experts, and policymakers to foster an integrated ecosystem supportive of DPP adoption. It also points out the necessity for significant investments in technology infrastructure, which poses a particular challenge for small and medium-sized enterprises (SMEs) due to their typically limited budgets and capacity.

In its conclusions, the thesis argues for a strategic approach that includes substantial government support and clear guidance, which is becoming increasingly important in light of new EU regulations that will require the mandatory adoption of DPPs. Through its detailed analysis and the expert insights gathered, the study not only enriches the academic discourse but also serves as a practical guide for industry practitioners and policymakers. By bridging these identified gaps, the recommendations provided could significantly influence future legislative developments and help streamline the implementation of DPP systems across Europe and beyond.

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## Appendix 1

### List of Tables



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## Appendix 2: ISSM Questionnaire

Subject: Request for Expert Participation in Research Study on Identifying Barriers to Implementing Digital Product Passports

Dear [Recipient's Name],

We are conducting a study entitled "Identifying Barriers to Implementing Digital Product Passports" and require your expert insight to achieve our research objectives. This study employs an ISM-MICMAC analytical approach to understand the interrelationships and the influence of various factors that affect the implementation of Digital Product Passports.

We kindly request a few minutes of your time to complete the attached questionnaire.

Below is a table designed to capture your perceptions as a professional or academic about the interactions between identified factors using an ISM-MICMAC approach. Please fill in the table using the following symbols to denote the relationships between each pair of factors:

V: Factor i leads to Factor j

A: Factor j leads to Factor i

X: Both Factor i and Factor j influence each other

O: Factors i and j are unrelated

| | j=F8 | F7 | F6 | F5 | F5 | F3 | F2 | F1 |
|---|---|---|---|---|---|---|---|---|
| i=F1 | | | | | | | | |
| F2 | | | | | | | | |
| F3 | | | | | | | | |
| F4 | | | | | | | | |
| F5 | | | | | | | | |
| F6 | | | | | | | | |
| F7 | | | | | | | | |
| F8 | | | | | | | | |

We greatly appreciate your time and expertise in helping us navigate this complex topic. Your insights are invaluable to our research and the broader understanding of Digital Product Passports' implementation barriers.

Thank you for your responsiveness and collaboration.

## Appendix 3

**DECLARATION**

**on authenticity and public assess of final essay/thesis/mater's thesis/portfolio[1]**

| | |
|---|---|
| Student's name: | Amia Elnaz |
| Student's Neptun ID: | CMITEY |
| Title of the document: | Identifying Barriers to Implementing Digital Product Passports |
| Year of publication: | 2024 |
| Department: | Institute of Agricultural and Food Economics, Department of Agricultural Logistics, Trade and Marketing |

I declare that the submitted final essay/thesis/master's thesis/portfolio[2] is my own, original individual creation. Any parts taken from an another author's work are clearly marked, and listed in the table of contents.

If the statements above are not true, I acknowledge that the Final examination board excludes me from participation in the final exam, and I am only allowed to take final exam if I submit another final essay/thesis/master's thesis/portfolio.

Viewing and printing my submitted work in a PDF format is permitted. However, the modification of my submitted work shall not be permitted.

I acknowledge that the rules on Intellectual Property Management of Hungarian University of Agriculture and Life Sciences shall apply to my work as an intellectulal property.

I acknowledge that the electric version of my work is uploaded to the repository sytem of the Hungarian University of Agriculture and Life Sciences.

Place and date: Budapest year 2024 month 04 day 18

Student's signature

Appendix 4

## Certification of participation in consultations

Name of the student: Elnaz Amia

Name of internal supervisor and position: Dr. Enikő Lencsés

Name of the independent organizational unit that published the topic:

In the 2023. / 2024 academic year, the nominated student regularly participated in the consultations related to the preparation of the diploma thesis. The completed dissertation (title)

**Identifying Barriers to Implementing Digital**
.........................................................................................
..................**Product Passports**

presented. I agree with the submission of the dissertation to the assessment procedure related to the Final Exam.

Gödöllő, 20... year ........................... month .................. day

.......................................

Sign of Supervisor