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Enhancing Transparency and Sustainability: Digital Product Passports

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Abstract:

How can companies ensure transparency in their supply chains while protecting sensitive data and meeting increasing demands for sustainability? Can digital product passports revolutionize industries, help reduce waste, optimize recycling and support a circular economy?

This report investigates the concept of DPPs and how they can provide visibility across a product's entire lifecycle, from raw material extraction to final disposal. Through blockchain integration, DPPs can make product data immutable and secure, offering businesses a way to manage their operations transparently without compromising competitive information.

#DPP #Blockchain #Transparency #Data

Enhancing Transparency and Sustainability:

Digital Product Passports

Aalborg University

Innovative Communication Technologies and Entrepreneurship

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1. Introduction

In the modern European market, the demand for transparency and sustainability in product manufacturing and consumption has reached unprecedented levels. Consumers are increasingly seeking detailed information about the products they purchase, including their origins, material composition, environmental impact, and potential for recycling or reuse. This shift is not a trend but a significant change in consumer behavior driven by greater awareness of environmental issues and a desire to make informed choices that align with personal and societal values. Recent research highlights that European consumers display strong environmental concern and are increasingly integrating sustainability into their purchasing decisions. According to Bassi (Bassi, F. 2023), approximately 90% of European citizens recognize environmental protection as important, with nearly 77% considering climate change a very serious issue at both national and European levels. Furthermore, a significant proportion of respondents express concerns about the impact of plastic products (48.2%) and microplastics (49.6%) on the environment, reflecting a broad societal shift towards more eco-conscious purchasing behavior.

In terms of sustainable consumption, over two-thirds (66.4%) of European consumers reported separating most waste for recycling, while 42.2% preferred purchasing locally produced goods to reduce environmental impact (Bassi, F. 2023).

The findings also emphasize the role of regulatory measures in shaping consumer behavior. While 55% of respondents believe environmentally friendly products provide good value for money, concerns about greenwashing persist, underlining the necessity for clear and verifiable sustainability claims. The increasing consumer demand for sustainability driven choices highlights the importance of Digital Product Passports as a tool to enhance product transparency, enabling consumers to make informed decisions based on reliable data regarding product origin, environmental footprint, and end-of-life management (Bassi, F. 2023)

The need for more transparent product information is not limited to consumers alone. Manufacturers, regulators, and other stakeholders in the supply chain also require access to accurate and comprehensive data to ensure compliance with increasingly stringent environmental regulations, optimize resource use, and reduce waste. The European Union has responded to these demands with a series of legislative initiatives aimed at promoting sustainability and circularity across the market. Central to these initiatives is the concept of the Digital Product Passport, a tool designed to provide all stakeholders with detailed information about a product throughout its lifecycle.

The Digital Product Passport is not just a technological innovation, it represents a fundamental shift in how products are tracked, managed, and marketed within the European market. DPPs offer a transparent, and secure way of documenting a product's journey from raw material extraction to manufacturing, distribution, use, and end-of-life. By providing this information in an accessible digital format, DPPs empower consumers to make more informed purchasing decisions and drive demand for more sustainable products.

The urgency of implementing Digital Product Passports is further underscored by the growing complexity of global supply chains and the increasing challenges associated with verifying product authenticity, compliance, and sustainability. In a market where products often pass through multiple hands before reaching the end consumer, the potential for misinformation, inefficiency, and environmental harm is significant. A report by the World Resources Institute highlights that the lack of transparency in global supply chains presents a significant challenge to achieving sustainability goals. Without clear visibility into sourcing practices, companies struggle to identify and mitigate environmental and social risks within their supply chains. This gap in traceability and data integrity underscores the necessity of a robust system like Digital Product Passports (DPPs), which can enhance accountability and provide stakeholders with reliable, real time sustainability information (WRI 2024).

The European Union's legislative framework, including the European Green Deal and the Circular Economy Action Plan (CEAP), places emphasis on the need for tools like DPPs to achieve the goal of making Europe the first climate neutral continent by 2050. The CEAP specifically calls for the development and implementation of Digital Product Passports as a means of ensuring that products placed on the EU market are sustainable by design and can

be reused, repaired, and recycled more effectively (European Commission, 2024). This approach not only supports environmental goals but also drives economic growth by fostering innovation and creating new business opportunities in the green economy.

The introduction of DPPs is meant to have a transformative impact on business practices across Europe. For manufacturers, DPPs provide a mechanism for demonstrating compliance with environmental regulations and for differentiating their products in a market that increasingly values sustainability. A report by McKinsey Global Institute highlights that European companies are facing a significant competitiveness gap compared to their U.S. counterparts, with digital transformation being a key factor in this disparity. To bridge this gap, the adoption of advanced digital tools, such as Digital Product Passports, is becoming increasingly critical for manufacturers. By improving resource tracking, optimizing supply chains, and enhancing transparency, DPPs can drive efficiency, reduce waste, and contribute to cost savings—factors that are essential for businesses striving to remain competitive in a rapidly evolving technological landscape (McKinsey & Company).

For consumers, the benefits of Digital Product Passports are equally compelling. In an era where misinformation and greenwashing are prevalent, DPPs provide a reliable source of truth, allowing consumers to verify the claims made by manufacturers and make choices that are aligned with their values. The ability to access detailed information about a product's environmental impact, material composition, and end-of-life options empowers consumers to take an active role in promoting sustainability. A study by Deloitte found that a growing number of European consumers are prioritizing sustainability in their purchasing decisions, with over 70% willing to pay a premium for products that are organic and sustainably sourced (Deloitte). Consumers are increasingly interested in understanding the environmental and social impact of their purchases, highlighting the need for greater transparency in supply chains. Digital Product Passports can play a crucial role in meeting this demand by providing detailed, reliable information about a product's origin, production processes, and sustainability credentials. This enhanced transparency fosters consumer trust and loyalty while encouraging more responsible consumption patterns.

1.1 Research Motivation

My way into the world of Digital Product Passports is fueled by an interest in blockchain technology and its potential to revolutionize various industries. Having previously worked on cases that utilize blockchain, I have witnessed firsthand the technology's power to drive significant environmental and economic benefits. This backdrop has naturally led me to explore DPPs.

The mandatory implementation of DPPs across the EU presents an urgent and fascinating challenge - to create systems that not only comply with legislation but also to make informed, sustainable choices in a globalized market. My motivation in writing this report stems from a desire to deeply understand how DPPs can be designed and deployed effectively, leveraging Blockchain to ensure data privacy, transparency, and integrity across diverse stakeholders.

By enhancing transparency and accountability in product life cycles, DPPs can help society at large make more informed decisions that support sustainable consumption and production patterns. This shift is vital in a world with the dual challenges of environmental degradation and resource scarcity. Through this report, I seek to contribute with knowledge that not only informs but also inspires action towards more sustainable industrial practices and consumer habits globally.

1.2 Project Formulation

"How can a blockchain-based Digital Product Passport balance data privacy and transparency to support circularity and sustainability?"

1.2.1 Research Questions

1. What are the key components and functions of a Digital Product Passport, and how do they contribute to sustainability and circularity?

2. How can blockchain technology be implemented within Digital Product Passports to ensure secure data management and interoperability across diverse supply chains?

3. How do external market and regulatory factors influence the adoption and strategic implementation of blockchain-based Digital Product Passports?

4. What architectural design principles are necessary for developing a blockchain based Digital Product Passport that balances data privacy with the need for transparency to support regulatory compliance and stakeholder trust?

1.3 Delimitations

This project sets clear boundaries to focus the scope of research and analysis. The primary focus is on investigating how Digital Product Passports can promote sustainability and support the circular economy within the context of a blockchain based system. The core objective is to investigate how such a system can balance data privacy with transparency, essential for both internal stakeholders and consumers. To maintain this focus, several delimitations were established.

The geographic focus of this project is limited to the European market. Given the European Union's strong push toward sustainability through regulatory initiatives such as the Circular Economy Action Plan, the EU was selected as the primary region of focus. This report does not explore the global market, as different regulatory landscapes and technological adoption rates would require more expansive research.

This project does not delve into the technical implementation details of blockchain systems or DPPs. Instead, the research is centered on the design principles necessary for creating a system that meets regulatory requirements while balancing privacy and transparency. .

The research is limited to current technology and regulations. While the study acknowledges the potential for future technological advancements, these developments are not included. Only existing EU regulations are considered. This decision was made to ensure that the report remains grounded in the present reality of DPP development.

1.4 Key Terms

- Digital Product Passport
- Sustainability
- Circular Economy
- Blockchain
- Data Privacy
- Transparency

2. Methodology

This chapter outlines the methodology to explore the development and implementation of a blockchain-based Digital Product Passport within the European market, with a particular focus on balancing data privacy, transparency, and sustainability. The methodology is performed to systematically address the research questions, ensuring the results are reliable, valid, and applicable within the context of European regulatory frameworks and market dynamics. The study primarily relies on the analysis of secondary data sources, including academic research papers, industry reports, and relevant EU regulatory documents.

2.1 Project Approach

Literature Review

The research began with a review of existing literature to establish a foundational understanding of Digital Product Passports and Blockchain Technology. This phase was crucial for mapping out the current landscape, understanding the technological and regulatory nuances, and identifying gaps in existing research. By examining scholarly articles, industry reports, and existing frameworks, a robust platform was set from which the project could delve deeper into more specific investigations.

Case Studies

Building on the literature review, the research methodology covers case studies of existing implementations of DPPs across various industries. Each case study was selected based on its relevance to the integration of blockchain technology and its demonstration of innovative practices or notable challenges. These case studies provided practical insights into the deployment, operation, and evolution of DPP systems, offering real world examples of both successes and challenges encountered by organizations.

Data Analysis

The collected data from literature and case studies underwent analysis to extract actionable insights and patterns. This process involved methods to understand the contextual nuances of each case and where applicable to measure impacts and efficiencies. This approach

ensured a comprehensive understanding of the dynamics at play in the implementation of DPPs and the role of blockchain technology therein.

Strategic Analysis

To align the technical findings with broader business and regulatory contexts, the project utilizes several strategic analysis tools. PESTEL analysis provided a macro environmental understanding of the factors influencing DPP adoption, while the Business Model Canvas helped visualize the value proposition and key partners, activities, and customer segments involved. Value Chain Analysis was used to dissect the steps involved in creating and delivering digital passports, identifying opportunities for optimization and innovation.

Architectural Design

The culmination of the research was the development of a proposed architectural design for a blockchain-based DPP system. The design was informed by all previous stages of the research, incorporating best practices, lessons learned, and future oriented strategies to ensure robustness, scalability, and capability of integrating emerging technologies. The design principles focused on security, privacy, interoperability, and compliance, aiming to provide a blueprint that could adapt to evolving technological landscapes and regulatory requirements.

2.2 Ethical Considerations

In conducting research and developing this project report, ethical considerations have been important to ensure that all investigative processes comply with the highest integrity and responsible research. The commitment to ethics is reflected in the attention to transparency, confidentiality, and respect for all data sources and participants involved in the study.

By incorporating ethical considerations into every stage of the methodology, from the initial literature review to the final design proposal, the research aims to not only contribute valuable insights to the field of digital product passports but also promote ethical standards that other researchers and practitioners can follow. This approach ensures that the findings and recommendations are not only technically sound and innovative but also socially responsible and aligned with broader societal values.

3. Literature Review

This chapter explores the existing research and development related to digital product passports, focusing on their role in promoting sustainability and circular economy. Through reviews of academic literature and industry reports, gaps are identified and the foundation for further analysis is laid.

3.1 What is a Digital Product Passport?

A Digital Product Passport is an innovative concept that is increasingly being recognized as a transformative tool in managing product information throughout a product's lifecycle (King, M. R., 2022). At its core, a DPP functions as a digital repository containing detailed and comprehensive information about a product, including its origin, materials, manufacturing processes, and its potential for reuse, recycling, or disposal. This repository is designed to be accessible to various stakeholders across the supply chain, including manufacturers, consumers, recyclers, and regulatory bodies, thereby fostering informed decision making that minimizes environmental impact and promotes resource efficiency.

The concept of a DPP is deeply intertwined with the principles of circularity and sustainability. As the global economy shifts towards more sustainable practices, the need for transparency in product lifecycle management has become important (King, M. R., 2022). A DPP addresses this need by providing an interoperable and accessible source of product information that can bridge the knowledge gap between different stakeholders. For manufacturers, a DPP offers a platform to document and share crucial information about the environmental footprint of their products (May, G. et al., 2024). This information is not only essential for regulatory compliance but also serves as a critical factor in gaining consumer trust. Consumers, on the other hand, can access this information to make more informed and sustainable purchasing decisions, aligning their consumption patterns with broader environmental goals.

Recyclers and waste management facilities can leverage the data within a DPP to optimize the recovery and reuse of materials, supporting the circular economy. The ability to trace materials and monitor their lifecycle is crucial for ensuring that products are not only used efficiently but are also disposed of in an environmentally responsible way. In this way, DPPs

contribute to closing the loop on resource use, ensuring that materials are kept in circulation for as long as possible and that waste is minimized (King, M. R., 2022).

A key feature of DPPs is their potential to integrate with advanced digital technologies like blockchain, which enhances the integrity, security, and immutability of the information contained within the passport. Blockchain technology, with its decentralized nature, offers a secure platform where product information can be recorded and accessed transparently, yet securely. This is particularly important in scenarios where data privacy and security are paramount, such as in the handling of proprietary information about product composition or sensitive data related to the environmental impact of production processes. By ensuring that this information is tamper proof, blockchain fosters trust among all stakeholders involved, further reinforcing the DPP's role in promoting sustainable practices.

DPPs are not static records; they are dynamic tools that evolve alongside the products they represent (King, M. R., 2022). As a product moves through its lifecycle - from raw material extraction to manufacturing, distribution, use, and end-of-life - new data can be added to the passport. This continuous updating ensures that the DPP remains a relevant and accurate reflection of the product's journey, providing real time insights into its sustainability credentials. This dynamic nature of DPPs also helps in identifying opportunities for improvement in product design and lifecycle management, enabling manufacturers to enhance the sustainability of their products over time.

The implementation of DPPs is seen as a step towards achieving the goals of Industry 5.0, where the focus shifts from automation and efficiency to sustainability and human centric innovation (May, G. et al., 2024). By embedding DPPs within the fabric of industrial processes, companies can better align their operations with the principles of the circular economy.

3.2 The Role of Digital Product Passports in promoting sustainability and circularity

Digital Product Passports play a role in advancing sustainability and circularity by facilitating more efficient and transparent management of products throughout their entire lifecycle.

Central to the concept of the circular economy is the idea that resources should be used more sustainably, with a focus on reducing waste, extending product life, and enabling the reuse, recycling, and recovery of materials (Lombardi, F. et al., 2023). DPPs are essential tools in achieving these objectives, as they provide a detailed digital record of a product's components, materials, and environmental impact, thereby supporting informed decision making across the supply chain.

One of the primary ways in which DPPs promote sustainability is by enhancing transparency (Lombardi, F. et al., 2023). By making detailed information about a product's materials, manufacturing processes, and potential for reuse and recycling accessible to all relevant stakeholders, DPPs enable manufacturers, consumers, and recyclers to make decisions that minimize environmental impact (Jansen, M. et al., 2023). For instance, when a product reaches the end of its life, the information stored in its DPP can guide recyclers on how to dismantle and recycle its components efficiently, ensuring that valuable materials are recovered and reused rather than discarded. This transparency is crucial for fostering a culture of sustainability where each participant in the product lifecycle can contribute to reducing the overall environmental footprint.

DPPs support circularity by facilitating the tracking and tracing of materials throughout the product life cycle. In industries such as electronics or footwear, where products often contain a mix of recyclable and non-recyclable materials, DPPs can help identify which parts can be recovered and reintroduced into the production cycle (Jansen, M. et al., 2022). By doing so, DPPs reduce the need for new materials and help decrease the environmental impact associated with material extraction and processing. The ability to trace materials back to their source, monitor their use, and understand their potential for future use is a significant step towards achieving a circular economy (Lombardi, F. et al., 2023).

DPPs also contribute to sustainability by encouraging better product design. When manufacturers know that their products will be accompanied by a DPP that records the environmental impact of each component, they are incentivized to design products with sustainability in mind. This might involve using more recyclable materials, designing for easier disassembly, or selecting processes that reduce energy consumption and emissions (Jansen, M. et al., 2023). The availability of this information in the DPP ensures that sustainability is

considered at every stage of the product life cycle, from design and manufacturing to end-of-life management (Jansen, M. et al., 2022). This proactive approach to product design is essential for creating products that are not only functional and cost effective but also environmentally responsible.

The implementation of DPPs is aligned with global regulatory trends that increasingly mandate greater transparency and accountability in product manufacturing (Lombardi, F. et al., 2023). As governments and international bodies push for more stringent environmental regulations, DPPs provide a mechanism for companies to demonstrate compliance with these standards (Jansen, M. et al., 2022). By integrating DPPs into their operations, companies can not only meet regulatory requirements but also gain a competitive advantage by positioning themselves as leaders in sustainability. This competitive edge is particularly important in today's market, where consumers are increasingly prioritizing sustainability in their purchasing decisions.

Digital Product Passports are tools in promoting sustainability and circularity. By enhancing transparency, supporting material tracking and tracing, encouraging better product design, and aligning with regulatory trends, DPPs help create a more sustainable and resource efficient economy (Lombardi, F. et al., 2023). Their adoption and implementation are critical for achieving the long term goals of the circular economy and ensuring that resources are used in a way that benefits both the environment and society (Jansen, M. et al., 2022).

3.3 GS1

According to GS1, a leading authority on global standards for supply chain management, DPPs are structured to improve transparency, traceability, and data accessibility, ensuring that products can be managed efficiently across their entire lifecycle (GS1, 2024). The GS1 framework emphasizes that "DPPs will provide a standardized way to share product information across the supply chain, enabling businesses to meet regulatory requirements and support sustainability goals." This underscores the importance of standardized data exchange in maintaining the integrity and utility of DPPs across diverse industries.

At the heart of a DPP is the unique product identification system, which is critical for maintaining the accuracy and traceability of the information associated with each product. GS1 explains that these identifiers, such as Global Trade Item Numbers (GTINs), are essential for linking products to their DPPs and ensuring that the data remains consistent and reliable as the product moves through different stages of its lifecycle (GS1, 2024). This unique identification is not only crucial for tracking the product but also for enabling interoperability between different systems and platforms. GS1 highlights that "standardized identifiers are key to ensuring that product information can be seamlessly exchanged across global supply chains," which is particularly important for industries with complex, multi-tiered supply chains.

In addition to unique identification, DPPs also contain detailed information about the product, including the materials used in its manufacture, the processes involved, and its environmental impact. GS1 notes that this information is crucial for assessing a product's sustainability credentials and for making informed decisions about its reuse, recycling, or safe disposal. The ability to trace materials and their environmental footprint throughout the supply chain is a cornerstone of the circular economy. According to GS1, "DPPs enable companies to track and trace materials from the point of origin to the end of life, ensuring that products are used more efficiently and that waste is minimized"(GS1, 2024). This transparency is not only crucial for regulatory compliance but also for building consumer trust and supporting sustainable business practices.

The dynamic nature of DPPs allows for continuous updating of information as the product progresses through its lifecycle. This ensures that the DPP remains an accurate and up-to-date reflection of the product's current status. GS1 underscores the significance of this feature by stating, "As products move through the supply chain, from production to end-of-life, their DPPs can be updated in real time to reflect changes in their status or composition." This capability is particularly important in industries where products undergo significant transformations, such as in electronics or automotive sectors. The ability to update the DPP dynamically supports better decision making and enhances the sustainability of the product over time.

3.4 EU REGULATION / LEGISLATION

The European Union has developed a comprehensive regulatory framework aimed at promoting sustainability, digital transformation, and circular economy practices (Dansk Standard, 2024). This framework includes various legislative initiatives, such as the Data Act, the Green Deal, and the Circular Economy Action Plan, which collectively set the stage for a more sustainable and digitally integrated economy. Specific regulations like the Ecodesign for Sustainable Products Regulation, Digital Product Passports, Green Claims, Corporate Sustainability Reporting Directive, and Sustainable Finance Disclosure Regulation play a crucial role in ensuring that companies operate transparently and responsibly.

- DATA ACT

The Data Act is a regulation within the EU's digital strategy, designed to unlock the potential of data across the European economy. It focuses on ensuring that data is shared more widely and fairly among businesses, governments, and citizens while maintaining high standards of privacy and security. The Data Act aims to create a single market for data, where data can be easily accessed and reused, fostering innovation and economic growth (Dansk Standard, 2024). This regulation is particularly relevant for Digital Product Passports as it ensures that the data necessary for the functioning of DPPs - such as product information, lifecycle data, and sustainability metrics - can be accessed and utilized by all relevant stakeholders in a secure and transparent manner. The Data Act supports the creation of a more transparent and data driven economy, which is essential for the successful implementation of DPPs and other digital initiatives aimed at promoting sustainability and circularity.

- GREEN DEAL

The European Green Deal is the EU’s strategy to make Europe the first climate neutral continent by 2050. It encompasses a wide range of policies aimed at reducing greenhouse gas emissions, promoting renewable energy, and fostering a circular economy. The Green Deal emphasizes the need for sustainable production and consumption patterns, which are supported by regulatory measures such as the Circular Economy Action Plan and the Ecodesign for Sustainable Products Regulation. The Green Deal also promotes the use of Digital Product Passports as a tool to enhance transparency and traceability across the supply

chain, enabling consumers and businesses to make more sustainable choices (Dansk Standard, 2024). By integrating DPPs into the Green Deal framework, the EU aims to ensure that products placed on the European market are designed with sustainability in mind, supporting the transition to a circular economy where resources are used efficiently and waste is minimized.

- CEAP

The Circular Economy Action Plan is a key component of the European Green Deal, focusing on the entire lifecycle of products with the aim of reducing waste and promoting the reuse, repair, and recycling of materials (Dansk Standard, 2024). CEAP outlines a series of measures to make sustainable products the norm in the EU, including the development of Digital Product Passports. DPPs are seen as essential tools within CEAP, enabling better tracking and management of products and materials throughout their lifecycle. The CEAP also includes proposals for legislative measures, such as the Ecodesign for Sustainable Products Regulation, which sets requirements for product sustainability, and the promotion of Green Claims, which ensures that environmental information provided by companies is accurate and verifiable. Through CEAP, the EU aims to build a sustainable and circular economy, where products are designed to last longer, be easier to repair, and be more recyclable.

3.4.1 Sustainability information and regulation

- ESPR

The Ecodesign for Sustainable Products Regulation is one of the EU's efforts to promote sustainable product design and production. The ESPR builds on the existing Eco-design Directive, expanding its scope to include a broader range of products and focusing not only on energy efficiency but also on other environmental aspects such as durability, reparability, and recyclability (Danak Standard, 2024). The regulation aims to ensure that products placed on the EU market are designed with their entire lifecycle in mind, minimizing their environmental impact from production to end-of-life.

Under the ESPR, manufacturers are required to provide detailed information about the environmental performance of their products, including data on energy consumption, material efficiency, and potential for reuse or recycling (Danak Standard, 2024). This information must be included in the product's Digital Product Passport, which serves as a comprehensive digital record of the product's lifecycle. By mandating the inclusion of this information in the DPP, the ESPR ensures that sustainability considerations are integrated into the design and production processes from the outset. This approach not only helps reduce the environmental impact of products but also supports the broader goal of transitioning to a circular economy, where resources are used more efficiently, and waste is minimized.

- GREEN CLAIMS

Green Claims refer to the environmental claims made by companies about the sustainability of their products or services. These claims are intended to inform consumers about the environmental benefits of a product, such as its reduced carbon footprint, use of recycled materials, or energy efficiency. The accuracy and reliability of Green Claims have come under scrutiny in recent years, leading to concerns about "greenwashing," where companies make exaggerated or misleading claims about the environmental performance of their products.

To address these concerns, the EU has introduced regulations to ensure that Green Claims are accurate, verifiable, and based on solid evidence (Danak Standard, 2024). Under these regulations, companies are required to substantiate their environmental claims with data and documentation that can be independently verified. This requirement is closely linked to the use of Digital Product Passports, which provide a standardized and transparent way to document and share the environmental performance of a product. By making this information readily available, DPPs help prevent greenwashing and ensure that consumers can trust the environmental claims made by companies.

- CSRD

The Corporate Sustainability Reporting Directive is another element of the EU's regulatory framework aimed at increasing transparency and accountability in corporate sustainability

practices. The CSRD requires large companies to disclose detailed information about their sustainability strategies, including how they manage environmental, social, and governance risks and opportunities. This disclosure must cover a wide range of topics, including carbon emissions, energy usage, water consumption, waste management, and human rights practices.

The CSRD builds on the existing Non-Financial Reporting Directive (Danak Standard, 2024), expanding its scope and introducing more reporting requirements. Under the CSRD, companies must provide this information in a standardized format, making it easier for investors, regulators, and other stakeholders to compare and evaluate the sustainability performance of different companies. The CSRD is closely aligned with the EU's broader sustainability goals, supporting the transition to a more sustainable economy by encouraging companies to adopt more responsible business practices.

The data provided in Corporate Sustainability Reports under the CSRD is increasingly being integrated with Digital Product Passports, enabling a more holistic view of a company's sustainability performance. By linking product level data with corporate level reporting, the CSRD and DPPs together provide a comprehensive framework for tracking and managing sustainability across the entire value chain.

- SFDR

The Sustainable Finance Disclosure Regulation is a component of the EU's sustainable finance agenda, which aims to direct capital towards more sustainable investments. The SFDR requires financial market participants, including asset managers, pension funds, and insurers, to disclose how they integrate sustainability risks into their investment decisions and how they consider the impacts of their investments on sustainability factors.

The SFDR is designed to increase transparency in the financial sector and to provide investors with the information they need to make informed decisions about the sustainability of their investments (Danak Standard, 2024). This regulation is particularly important for aligning

financial flows with the EU's sustainability goals, ensuring that capital is allocated in a way that supports the transition to a low carbon, resource efficient economy.

The SFDR works in tandem with other EU regulations, such as the CSDR and the EU Taxonomy, which provides a classification system for sustainable economic activities. Together, these regulations create a comprehensive framework for sustainable finance, ensuring that sustainability considerations are integrated into every aspect of the financial system.

3.5 Blockchain as an enabler of Digital Product Passport

The implementation of Digital Product Passports (DPPs) is a key pillar of the European Union's sustainability and circular economy agenda, as outlined in the European Green Deal and the Ecodesign for Sustainable Products Regulation (ESPR). These policies mandate the integration of DPPs to enhance product traceability, material circularity, and regulatory compliance. However, traditional digital data management systems face limitations regarding data integrity, interoperability, and security (Falco, 2023). Blockchain technology has emerged as a foundational enabler of DPPs, offering an immutable, transparent, and decentralized infrastructure that ensures data authenticity and verifiability throughout global supply chains (Jansen et al., 2022).

A central challenge in ensuring the effectiveness of DPPs is maintaining the accuracy and reliability of product information throughout its lifecycle. Blockchain's decentralized structure guarantees that once data is recorded, it cannot be altered without detection, ensuring tamper proof product records (King et al., 2022). This is particularly relevant for industries where sustainability claims must be independently verifiable, such as electronics, textiles, and battery manufacturing (Lombardi et al., 2023). Unlike centralized databases, which are vulnerable to manipulation, security breaches, and single points of failure, blockchain operates as a distributed ledger system, eliminating the risk of unauthorized modifications or data loss (Jansen et al., 2022). This resilience is particularly crucial in regulatory environments that demand transparent sustainability reporting, such as the EU Battery Regulation, which requires manufacturers to track raw material sourcing and environmental impacts. The decentralized validation mechanisms of blockchain ensure that product data is independently

verified by multiple participants before being added to the ledger, strengthening accountability and trust in sustainability reporting (Psarommatis & May,G., 2024).

One of blockchain's most significant contributions to DPPs is its ability to provide end-to-end product traceability, ensuring that every stage of a product's lifecycle - from raw material extraction and production to distribution, consumer use, and end-of-life recycling - is securely documented and accessible (Jansen et al., 2022). This continuous flow of verifiable data is particularly crucial in the circular economy, where companies are required to demonstrate that materials are reused, repurposed, or recycled rather than discarded as waste (Lombardi et al., 2023). Blockchain enables granular tracking of key product attributes, such as material composition, ethical sourcing certifications, and environmental impact assessments. Through blockchain-enabled decentralized identifiers (DIDs) and verifiable credentials, DPPs provide real time, authenticated sustainability data to regulators, manufacturers, and consumers, ensuring transparency and trust across supply chains (Psarommatis & May, 2024). This level of traceability not only supports corporate sustainability commitments but also aligns with the increasing consumer demand for greater transparency in product sourcing and environmental footprint.

Beyond data integrity and traceability, blockchain also enhances regulatory compliance and automation through smart contracts—self-executing agreements embedded in blockchain networks that automatically enforce and verify contractual terms (Falco, 2023). Smart contracts allow DPPs to automate key sustainability processes, such as ensuring regulatory compliance before market entry, automated tracking of carbon footprint thresholds, and initiating recycling incentives when products reach end-of-life (King et al., 2022). By embedding sustainability regulations directly into digital product frameworks, blockchain-based automation reduces administrative overhead, ensures compliance consistency, and enhances operational efficiency.

Although blockchain enhances transparency in product lifecycle data, concerns remain regarding data privacy and proprietary information security. Companies handling sensitive supply chain data fear that public access to blockchain records could expose trade secrets or competitive advantages (Lombardi et al., 2023). However, blockchain integrates privacy enhancing technologies (PETs) that allow controlled access to sensitive data while maintaining

compliance with data protection regulations, such as GDPR and the EU Data Act (Jansen et al., 2022).

As industries expand their sustainability initiatives, the scalability of DPPs becomes increasingly important. Blockchain enables large scale deployment of DPPs while maintaining high speed data processing, security, and compliance adaptability (King et al., 2022). Its distributed ledger architecture allows for decentralized data management across global supply chains, eliminating single points of failure and ensuring continuous access to sustainability records (Jansen et al., 2022). Blockchain's interoperability with existing digital ecosystems ensures that different DPP platforms can communicate, and exchange verified data seamlessly, addressing the growing need for cross industry collaboration in sustainability reporting. As regulatory frameworks continue to evolve, blockchain provides a flexible, regulatory ready infrastructure that allows companies to meet new compliance requirements without significant system overhauls.

Blockchain is not merely an enhancement to Digital Product Passports - it is a foundational enabler that ensures trust, security, and automation in compliance with mandatory sustainability regulations. By securing product lifecycle data, strengthening transparency, and enabling automated compliance mechanisms, blockchain allows DPPs to function as reliable and scalable solutions for companies integrating sustainability and circular economy principles into their operations. As DPP adoption becomes a regulatory necessity, blockchain will continue to play a pivotal role in supporting companies in meeting compliance obligations while maintaining a competitive advantage in sustainability driven markets.

3.6 Privacy and Security in Digital Product Passports

The implementation of Digital Product Passports presents essential privacy and security challenges, particularly as these systems become a requirement under various regulatory frameworks. As DPPs are designed to improve transparency and traceability across product lifecycles, they must also safeguard sensitive business information, intellectual property, and compliance with data protection regulations (Ducuing et al., 2023). Ensuring that DPPs strike

a balance between openness and confidentiality is crucial for their successful adoption across industries.

A key challenge in DPP implementation is determining how much product related information should be publicly accessible and to whom. Regulatory bodies, consumers, and sustainability organizations advocate for greater transparency in supply chains, particularly in industries with high environmental and social impact, such as textiles, electronics, and battery production (CIRPASS, 2024). However, business sensitive data, including supplier relationships, production methodologies, and proprietary material compositions, must be protected from unauthorized disclosure (Jansen et al., 2022). Excessive transparency could expose companies to intellectual property theft, loss of competitive advantage, and supply chain disruptions, making it essential to implement controlled disclosure mechanisms that differentiate between mandatory transparency for compliance and confidential business data (Langley et al., 2023).

The General Data Protection Regulation (GDPR) and the EU Data Act impose strict guidelines on how data is collected, stored, and accessed, which has direct implications for DPP systems (Ducuing et al., 2023). Under these regulations, companies must ensure that only relevant and necessary data is shared, preventing excessive disclosure that could compromise privacy rights or business confidentiality. This requirement highlights the need for a well structured approach to data governance, ensuring that DPPs serve their purpose of increasing transparency without creating additional risks.

To navigate these concerns, clear governance frameworks must define who owns the data within a DPP, how access is granted, and under what conditions information can be shared (Jansen et al., 2022). Companies operating in global supply chains must consider regional variations in privacy laws, as data sharing policies and legal obligations may differ across jurisdictions. Establishing uniform guidelines that align with international regulatory frameworks is necessary to avoid legal uncertainties and ensure smooth interoperability between different stakeholders (CIRPASS, 2024).

Beyond regulatory considerations, companies must also safeguard against risks such as unauthorized data access, supply chain disruptions, and external threats. Ensuring that DPPs remain secure throughout their lifecycle is fundamental to maintaining trust among

stakeholders (Langley et al., 2023). Businesses must establish clear policies on data ownership and define who is responsible for maintaining, updating, and verifying the accuracy of product information (Ducuing et al., 2023). Without structured data governance models, organizations risk legal uncertainty and difficulties in managing cross border data exchanges.

Interoperability between DPP systems across industries is another important consideration. Different sectors may require varying levels of data access and security, depending on product complexity and regulatory demands (CIRPASS, 2024). Ensuring compatibility across supply chain networks is necessary to avoid fragmentation and inefficiencies when DPPs are adopted on a broader scale. By aligning data sharing standards with industry best practices, companies can develop solutions that respect privacy while maintaining compliance with global reporting requirements (Jansen et al., 2022).

As the regulatory landscape evolves, privacy and security concerns in DPP adoption will remain central to discussions on digital transparency. Companies must take a proactive approach to managing risks, ensuring that confidentiality is preserved while meeting transparency goals. Developing practical strategies for controlled data access, industry wide alignment on governance standards, and compliance with legal obligations will be essential for ensuring DPPs fulfill their role without introducing unnecessary security or privacy vulnerabilities. As industries continue to implement and refine digital product tracking systems, maintaining a careful balance between openness and confidentiality will be critical to their long term success.

3.7 Sub Conclusion

The Literature Review highlights the transformative potential of Digital Product Passports in advancing sustainability and circular economy practices. DPPs function as digital repositories, enabling stakeholders across the supply network to access critical product information. This accessibility fosters informed decision making that supports environmental sustainability. Key elements such as blockchain integration enhance the security and transparency of the information, ensuring data integrity and compliance with regulatory standards. The review underscores the role of DPPs in reducing waste, enhancing resource efficiency, and driving sustainable product lifecycle management, making them crucial tools in achieving global sustainability goals.

4. Case Studies

This chapter investigates several case studies to examine the practical application of Digital Product Passports across various industries. By analyzing these examples, the aim is to highlight both the challenges and successes, providing valuable insights that will inform the design and strategic recommendations later in this report.

4.1 CIRPASS

The CIRPASS project represents a significant initiative within the European Union aimed at establishing a harmonized framework for Digital Product Passports (DPPs). As industries transition towards mandatory digital product tracking under the Ecodesign for Sustainable Products Regulation (ESPR) and other EU sustainability policies, CIRPASS plays a pivotal role in defining the technical, regulatory, and interoperability standards necessary for widespread DPP implementation. Bringing together over 30 organizations from the fields of manufacturing, technology, and research, the project fosters cross-sectoral collaboration to address the complexities associated with DPP deployment while ensuring alignment with both regulatory compliance requirements and practical industry needs (CIRPASS, 2024).

A key focus of CIRPASS is the electronics, textiles, and plastics industries, sectors that face increasing regulatory pressure to enhance sustainability and transparency. These industries are among the most resource intensive in Europe, and ensuring the efficient tracking of product lifecycle data is essential for achieving circular economy objectives. CIRPASS is actively engaged in pilot projects within these sectors, testing the feasibility of DPP adoption in real world scenarios. These pilot studies are crucial for identifying technical and operational challenges that companies may face when integrating DPPs into their supply chains. By conducting these tests, CIRPASS is not only developing theoretical models but also ensuring that DPP solutions are practically viable, scalable, and aligned with the realities of industrial operations (CIRPASS, 2024).

One of the defining strengths of CIRPASS is its inclusive approach to stakeholder engagement. Recognizing that the successful adoption of DPPs depends on widespread industry collaboration, the project involves policymakers, industry leaders, consumer representatives, and sustainability advocates. This approach ensures that the framework developed through

CIRPASS reflects the diverse needs of all stakeholders, reducing friction between regulatory mandates and industrial adoption. By fostering collaboration between regulatory bodies and businesses, CIRPASS seeks to streamline compliance processes, align industry practices with EU sustainability policies, and remove adoption barriers (CIRPASS, 2024).

Standardization is a critical objective of CIRPASS. One of the major challenges in implementing DPPs across industries is ensuring interoperability between different digital systems and supply chain networks. CIRPASS is working to create common standards that will allow seamless data exchange between businesses, regulators, and consumers while ensuring data security and privacy compliance. A standardized cross-sectoral data model will facilitate the identification, classification, and traceability of materials and components, allowing companies to integrate DPPs into their operations without significant disruptions. Furthermore, CIRPASS is defining a product identification framework, establishing clear guidelines for product tracking across its entire lifecycle to support sustainability reporting, regulatory enforcement, and circular economy strategies (CIRPASS, 2024).

Ensuring that CIRPASS provides long term value requires forward thinking strategies that anticipate future regulatory and technological developments. As digital and regulatory landscapes evolve, CIRPASS aims to create a flexible and future proof framework that remains adaptable to new compliance requirements and emerging technologies. The project's focus on data governance and security will be essential for addressing concerns related to intellectual property protection, cybersecurity risks, and compliance with GDPR and the EU Data Act. CIRPASS is also working on an open DPP data exchange protocol, ensuring that stakeholders can securely share product related information while protecting sensitive business data (CIRPASS, 2024).

The expected outcomes of CIRPASS are projected to have a substantial impact on both EU policy and industrial practices. By providing a structured blueprint for DPP implementation, CIRPASS will likely influence the development of future EU regulations and industry standards, guiding companies towards greater transparency and sustainability compliance. The lessons learned from CIRPASS pilots and stakeholder collaborations will serve as a valuable reference for other industries and global markets looking to adopt similar digital product tracking

frameworks. Europe's leadership in DPP standardization may set a precedent for global best practices, positioning the EU at the forefront of digital sustainability governance.

By refining and formalizing the technical, legal, and operational aspects of DPPs, CIRPASS is laying the foundation for the seamless integration of digital product passports across European industries. Through its emphasis on regulatory alignment, industry wide adoption, and technological interoperability, CIRPASS is shaping the future of product lifecycle transparency and circular economy integration.

4.1.1 Goals and Objectives

The CIRPASS project has set out several core objectives to advance the implementation of Digital Product Passports across key sectors such as batteries, electronics, and textiles. These objectives are central to the project's mission of promoting a circular economy and enhancing product transparency across Europe.

1. **Establish a Cross-Sectoral Definition and Framework for DPPs**
   CIRPASS seeks to develop a clear and universally accepted definition of what constitutes a Digital Product Passport. By creating a standardized framework applicable across multiple industries, CIRPASS ensures regulatory alignment and consistency in DPP adoption, preventing fragmentation and improving clarity among stakeholders (CIRPASS, 2024).

2. **Develop a Comprehensive Product Data Model for Circular Economy Use Cases**
   The project aims to create a structured and standardized product data model that integrates key sustainability indicators, lifecycle tracking data, and regulatory compliance information. This model will facilitate efficient product identification, material traceability, and enhanced recyclability, ensuring that DPPs contribute directly to circular economy goals (CIRPASS, 2024).

3. **Define Standardized Methods for Product Identification and Tracking**
   CIRPASS is working on establishing a unified system for product identification throughout its lifecycle, enabling seamless tracking from production to disposal or reuse. This effort includes aligning with existing product labeling standards (e.g., GS1, RFID, NFC) and emerging digital identification technologies, ensuring that DPPs can be accurately referenced across global supply chains (CIRPASS, 2024).

4. **Develop an Open DPP Data Exchange Protocol**
   A key focus of CIRPASS is the creation of an open, interoperable data exchange protocol that enables secure, real time sharing of product information between manufacturers, regulators, recyclers, and consumers. This protocol will be designed to ensure data security, privacy compliance, and adaptability to future technological advancements, reinforcing data transparency while protecting business sensitive information (CIRPASS, 2024).

5. **Facilitate Stakeholder Consensus on Essential Data Requirements and Standardized Vocabulary**
   CIRPASS aims to harmonize data formats and language standards across industries, ensuring that DPPs use a consistent set of data fields and terminology. By working towards European and globally recognized vocabulary standards, the project helps prevent misalignment between sectors, enhancing the interoperability and reliability of DPP systems (CIRPASS, 2024).

6. **Develop Roadmaps and Use Cases for Large-Scale DPP Piloting and Adoption**
   To accelerate real world adoption, CIRPASS is developing roadmaps, pilot programs, and deployment strategies that demonstrate the business value and regulatory benefits of DPPs. These efforts aim to provide companies with practical guidance on integrating DPPs into their operations, reducing uncertainty and streamlining implementation efforts (CIRPASS, 2024).

4.2 IKEA

The case study on IKEA's transition towards a circular economy (Szerakowski, C., 2017) provides critical insights into how large corporations can adopt sustainable practices, and how this framework can inform the design of Digital Product Passport architectures. Although the case study is focused on IKEA, the principles and methodologies discussed offer broader lessons that can be applied to the development of DPP systems, particularly in industries where transparency, data security, and sustainability are becoming mandatory due to regulatory pressures.

The methodology employed in this study uses a backcasting approach, a strategic planning method where desired future outcomes are envisioned, and steps to achieve these outcomes are developed in reverse order. In the context of IKEA, this meant setting long term sustainability goals for 2025 and identifying the steps needed to transition from their current state to a fully circular business model. This concept can be directly applied to DPPs, where companies must define their end goals for transparency and sustainability (which will be mandatory by 2027-2028 in the EU) and work backward to develop the necessary technical and regulatory frameworks. This approach ensures that the architecture you design for DPPs is robust, forward looking, and scalable, aligning with long term sustainability goals (Szerakowski, C., 2017).

A key takeaway from the IKEA study is the integration of circular design principles into the product development process. For IKEA, this meant creating products that were durable, repairable, and easy to disassemble for recycling. The same principle applies to DPP architecture, which must be designed to document and track the materials and components of a product throughout its lifecycle. This can be achieved by integrating blockchain and other technologies like QR codes and RFID chips to ensure that product data is immutable and accessible at all stages. The case study highlights the importance of modularity in design, ensuring that products (or in the case of DPPs, systems) can be updated and scaled as needed, without having to be completely overhauled (Szerakowski, C., 2017). This modularity can ensure that DPPs remain future proof as regulations and technologies evolve.

The case study also emphasizes the necessity of stakeholder engagement throughout the transition process. For IKEA, this involved collaborating with suppliers, customers, and regulators to ensure that their circular economy goals were achievable and aligned with broader industry practices. Similarly, the architecture of a DPP system must involve input from a wide range of stakeholders, including manufacturers, regulators, and consumers. Each stakeholder has different needs: manufacturers need to ensure data security and traceability; regulators require transparency to ensure compliance with sustainability laws; and consumers demand access to product information that influences their purchasing decisions. By ensuring that the DPP architecture addresses these diverse needs, you create a more holistic and adaptable system. The importance of collaboration between stakeholders is a recurring theme in the case study and serves as a fundamental pillar for the success of DPP implementations.

In terms of technological integration, the case study discusses how IKEA incorporated advanced technologies like IoT (Internet of Things) and data analytics to track product usage and performance throughout its lifecycle (Szerakowski, C., 2017) . In the context of DPPs, technology integration is critical for ensuring that product data is continuously updated and accurate. Blockchain technology can provide a decentralized, secure platform for recording product data, while IoT devices can track real time usage and environmental conditions, feeding this data into the DPP system. QR codes and RFID chips allow for easy access to product information at any stage in the supply chain, ensuring that data remains accessible and actionable. By designing an architecture that integrates these technologies, you can create a DPP system that enhances transparency and promotes sustainability, in much the same way that IKEA's technology strategy enhances their circular business model.

One of the most relevant aspects of the case study was the focus on regulatory compliance. IKEA's transition was driven, in part, by the need to comply with evolving environmental regulations, particularly within the European Union. For companies implementing DPPs, compliance with regulations like the EU's Sustainable Products Initiative and General Data Protection Regulation (GDPR) will be crucial. The architecture of the DPP system must ensure that data is handled in a way that complies with privacy laws and that product information is accessible to regulators for monitoring sustainability practices. The study points out that

regulatory pressure can serve as a catalyst for innovation, pushing companies to adopt more sustainable and transparent practices. By building a DPP architecture that is compliant with these regulations, companies can not only avoid legal penalties but also gain a competitive advantage by positioning themselves as leaders in sustainability.

4.3 The Battery Pass

The Battery Pass project is an essential initiative within the European Union, focusing on the development and implementation of Digital Product Passports for batteries, supporting the broader goals of the circular economy. This project plays a critical role in ensuring that batteries are traceable, sustainable, and compliant with the European Union's growing regulatory framework aimed at promoting circularity and reducing environmental impact. As Europe moves towards an electrified and sustainable economy - especially with the rise of electric vehicles and renewable energy storage - batteries have become a focal point in this transition. The Battery Pass project was established to address the challenges of managing battery life cycles in a sustainable way, ensuring that key data on battery materials, usage, and disposal is transparent, accessible, and secure.

The Battery Pass project is primarily driven by new EU regulations that are part of the broader European Green Deal. The Green Deal aims to make Europe the first climate neutral continent by 2050 and mandates sustainable practices across industries, including the battery sector. The EU recognizes the environmental and social impact of battery production, especially in terms of raw material sourcing, carbon emissions during manufacturing, and end-of-life waste management (The Battery Pass, 2024). The project is also a response to the EU's Battery Regulation, which will require batteries placed on the market to meet strict criteria related to sustainability, transparency, and recyclability by 2027.

The initiative focuses on creating a Digital Product Passport for batteries, which will serve as a comprehensive digital record of a battery's life cycle. This DPP will include critical information such as the origin of raw materials, the carbon footprint of production, the conditions under which the battery has been used, and how it can be recycled or disposed of at the end of its life (The Battery Pass, 2024). The primary purpose of the project is to create

a digital infrastructure that supports these requirements, facilitating compliance with EU regulations while promoting circularity and transparency within the battery industry.

The Battery Pass project serves as a flagship example of how DPPs can be implemented in a specific industry - batteries. The project addresses several key issues within the battery supply chain, focusing on ensuring transparency and sustainability through lifecycle data tracking, standardization, and real time access to information. One of the primary challenges in the battery sector is the sourcing of raw materials such as lithium, cobalt, and nickel, which often involve environmentally damaging practices or human rights violations in mining operations. The DPP developed by Battery Pass will provide detailed information on the origin and environmental footprint of these materials, allowing stakeholders to ensure that batteries meet sustainability standards (The Battery Pass, 2024).

A critical component of the Battery Pass project is lifecycle data tracking, which ensures that batteries are traceable from the point of raw material extraction through manufacturing, usage, and disposal. This feature is essential for promoting circularity, as it provides data on how batteries are used and how they can be recycled or repurposed at the end of their life. The inclusion of detailed lifecycle data helps regulators, manufacturers, and consumers make informed decisions about how batteries are produced and consumed (The Battery Pass, 2024). In the context of your project, the integration of continuous data tracking across the supply chain is a valuable design principle that ensures transparency and sustainability throughout a product's lifecycle.

Another key aspect of the project is data standardization. Given the complexity of the battery supply chain, which involves multiple stakeholders across different regions and industries, it is essential to create standardized formats for data collection and reporting. The Battery Pass project emphasizes the need for interoperability between different data systems, ensuring that information can be easily shared and accessed by all relevant actors (The Battery Pass, 2024). This standardization aligns with the broader goals of the circular economy, as it enables the seamless exchange of data across supply chains, improving efficiency and promoting collaboration among stakeholders.

The Battery Pass project also utilizes blockchain technology to secure and store data within the DPP. Blockchain provides an immutable ledger that ensures the integrity and transparency of data, making it a key technology for ensuring that battery data cannot be tampered with. Blockchain's decentralized nature also provides trust among stakeholders, as all parties have access to the same data, reducing the likelihood of disputes or misinformation (Battery Pass, 2024). This principle of using blockchain for data security and transparency is particularly relevant for your project's architecture, as it underscores the importance of integrating secure and tamper proof systems into DPPs.

The project further highlights the importance of real time data access. By ensuring that data is updated continuously, the Battery Pass allows manufacturers and regulators to monitor battery performance and compliance with sustainability standards in real time. This feature enables proactive decision making, allowing companies to address any potential issues related to sustainability or regulatory compliance before they become problematic (The Battery Pass, 2024). Real time data access also supports the long term management of batteries, as it provides insight into their condition, helping to determine whether a battery should be repurposed, recycled, or disposed of.

The collaboration between stakeholders is a building block of the Battery Pass project. The initiative involves multiple actors, including battery manufacturers, recyclers, regulatory bodies, and even consumers. By facilitating collaboration across these stakeholders, the project ensures that the DPP system is aligned with the needs of all parties involved in the battery life cycle (The Battery Pass, 2024). This collaborative approach is critical to the success of the project, as it ensures that data is shared transparently and that all actors can contribute to the sustainability of the battery industry.

The architecture of the Battery Pass DPP is built on several core design principles that ensure the system is secure, transparent, and adaptable. The first principle is lifecycle data tracking, which allows the DPP to monitor the entire lifecycle of a battery. This feature ensures that data related to material sourcing, manufacturing, usage, and recycling is continuously updated and accessible. By tracking this data, the DPP can provide real time insights into the environmental impact of batteries, helping companies comply with EU sustainability regulations.

Another critical design principle is data standardization and interoperability. The Battery Pass project recognizes the complexity of the battery supply chain and the need for standardized data formats that can be shared across industries and regions. To address this, the DPP system is designed to support standardized data entry and reporting, ensuring that information can be easily exchanged between different actors in the battery life cycle. This standardization is essential for promoting collaboration and ensuring that all stakeholders have access to the same information.

Blockchain technology is at the heart of the Battery Pass DPP's architecture. By using blockchain, the system ensures that data is secure, transparent, and immutable. Blockchain's decentralized nature provides a shared ledger for all stakeholders, reducing the risk of tampering or disputes over data. This technology is particularly important for ensuring trust in the system, as it guarantees that all data related to the battery's life cycle is accurate and cannot be altered without detection.

The system also incorporates real time data access as a core feature. This ensures that data is continuously updated, providing stakeholders with up-to-date information on battery performance and sustainability (The Battery Pass, 2024). Real time data access is essential for ensuring that companies can monitor their compliance with EU regulations and address any sustainability issues as they arise. It also supports long term battery management, helping companies make informed decisions about whether to repurpose, recycle, or dispose of batteries.

5. Data Analysis

This chapter presents the findings from the data collection, examining the implementation and impact of Digital Product Passports through specific case studies. Analyzing the data to uncover trends, challenges, and opportunities, providing empirical insights.

The integration of Digital Product Passports across different industries presents a compelling story about their role in driving sustainability and circular economy principles. A detailed examination of three case studies - IKEA's transition towards a circular economy, the CIRPASS project, and the Battery Pass project - provides deep insights into the operationalization of DPPs and their transformative impacts. This analysis combines the key data points from each case to identify overarching themes and distinct practices that underline the varied applications of DPPs.

IKEA's strategic approach to sustainability involves a comprehensive redesign of products to enhance their lifecycle, increase the use of recycled materials, and reduce waste across all operations. This case exemplifies how a global retailer can implement sustainability through every layer of product management, from design to consumer use, and ultimately, recycling. In contrast, the CIRPASS project takes a more focused approach by aiming to standardize DPPs across the electronics and textiles sectors. This initiative is noteworthy for its attempt to define a cross-sectoral product data model that can significantly improve lifecycle transparency and facilitate better recycling and reuse practices.

The Battery Pass project specifically addresses the sustainability challenges within the battery industry by developing DPPs that ensure complete traceability and compliance with stringent EU regulations. Utilizing blockchain technology, this project emphasizes the security and integrity of data, which is crucial for maintaining transparency and trust across the battery's lifecycle from production to disposal.

Across these case studies, several themes emerge that are critical to the success of DPPs. Technological integration is a cornerstone, with each case leveraging digital tools to enhance the functionality and reliability of DPPs. Whether it's blockchain in the Battery Pass or various digital platforms in IKEA's operations, technology underpins the ability to track, manage, and share product information securely and efficiently. Another key theme is stakeholder

engagement, which is essential for the adoption and effective implementation of DPPs. Each project demonstrates a collaborative effort to include a range of stakeholders, from manufacturers and consumers to recyclers and regulatory bodies, ensuring that all voices are considered in the development and execution of DPP strategies.

Regulatory compliance and alignment with sustainability goals also play important roles. Each case study aligns its DPP initiatives with specific regulatory requirements and broader sustainability objectives, which not only ensures legal compliance but also supports the global transition towards more sustainable practices. The facilitation of the circular economy is perhaps the most significant theme, with DPPs enabling better resource efficiency through improved traceability and lifecycle management.

Despite these common themes, the case studies also reveal notable differences, particularly in the scope of impact, technological utilization, and regulatory influence. IKEA's broad application across a wide range of consumer goods contrasts with the more targeted technological and regulatory focus of the Battery Pass and CIRPASS projects. These differences show the gaps that may exist in the universal application of DPPs and highlight potential areas for further research or adjustment, such as exploring diverse technological solutions beyond blockchain or adapting DPP frameworks to varying regulatory landscapes.

This comparative analysis not only highlights the unique and shared characteristics of DPP implementation across different sectors but also sets the stage for a deeper exploration of how these principles can be universally applied to foster sustainability and circularity. The insights gained from this, provide a robust foundation for the analysis and design chapter, ensuring that the recommendations and frameworks developed are deeply informed by empirical evidence and real world applications. This approach ensures that the data analysis is not only thorough but also directly applicable to practical and strategic decision making in the context of Digital Product Passports.

6. Strategic Analysis

The objective of this chapter is twofold. First, to articulate a detailed system architecture that meets the rigorous demands of various stakeholders, including manufacturers, regulators, and consumers, all of whom require accurate and timely information on product provenance and environmental impact. Second, to present a clear and robust requirements specification that encapsulates both functional and non-functional aspects, ensuring that the DPP system not only aligns with current technological capabilities but also adapts to future advancements and regulatory changes.

Drawing on insights from the Business Model Canvas and Value Chain Analysis, this chapter will demonstrate how the DPP system integrates into broader business operations, enhancing value creation while promoting a circular economy. By linking these components cohesively, the design presented, not only addresses the immediate operational needs but also sets a path for scaling and evolution.

6.1 PESTEL

A PESTEL analysis provides a strategic framework to understand the external factors (Akbalik, M. et al., 2020) influencing the integration and implementation of Digital Product Passports within the European market. This analysis evaluates Political, Economic, Social, Technological, Environmental, and Legal factors, offering insights into the broader environment that will shape the success and challenges of DPP adoption.

Political Factors

The political landscape in Europe is highly conducive to the adoption of Digital Product Passports, driven primarily by the European Union's commitment to sustainability and transparency. The European Green Deal and the Circular Economy Action Plan are central to these efforts, with the EU setting ambitious goals to achieve climate neutrality by 2050. These initiatives have led to the introduction of regulatory frameworks that will soon mandate the use of DPPs for certain products, particularly those that have significant environmental impacts, such as electronics and batteries (European Commission, 2025).

The European Green Deal, for instance, emphasizes the need for enhanced product transparency and resource efficiency, both of which are directly supported by DPPs. The European Commission's proposal for the Sustainable Products Initiative outlines the political commitment to making DPPs a legal requirement for various products, aiming to ensure that consumers have access to detailed information about the sustainability of the products they purchase (European Commission, 2022). These regulations are part of a broader political agenda to promote sustainable consumption and production, which creates a favorable environment for the integration of DPPs across industries.

The EU's regulatory environment ensures consistency across member states, minimizing the risk of legal discrepancies that could complicate the adoption of DPPs. This political stability and the EU's strong commitment to sustainability goals provide a solid foundation for companies to invest in DPP systems, knowing that they align with long term policy directions (European Commission, 2025).

Economic Factors

The economic implications of implementing DPPs are multifaceted. On the one hand, there are significant initial costs associated with the adoption of DPPs, including investments in blockchain technology, data management systems, and compliance mechanisms. However, these upfront costs can be offset by the long term economic benefits that DPPs offer, such as enhanced supply chain efficiency, reduced waste, and improved resource management (Ellen MacArthur Foundation, 2022).

The shift towards a circular economy, which is heavily promoted by the European Union, also opens up new economic opportunities for companies that adopt DPPs. By enabling more efficient recycling, reuse, and resource recovery, DPPs can help companies reduce their reliance on raw materials, lower production costs, and improve their overall sustainability footprint. This is particularly relevant in industries like electronics, where the environmental impact of products is significant, and where DPPs can play a critical role in managing end-of-life processes (WBCSD, BCG 2023).

As consumers become more environmentally conscious, there is a growing market for products that are transparent about their sustainability credentials. Companies that invest in

DPPs can leverage this demand, offering premium products that are verified as sustainable, which can enhance brand reputation and open up new revenue streams.

Social Factors

Social factors, particularly the evolving attitudes and behaviors of consumers, are crucial in driving the adoption of DPPs. There is a clear trend towards greater consumer demand for transparency in the products they purchase, with increasing emphasis on sustainability, ethical sourcing, and environmental impact. This shift is not just a trend but a significant societal change that influences purchasing decisions across various demographics (NIQ, 2025).

Moreover, as consumers become more aware of global environmental challenges, they are more likely to support brands that align with their values. This societal shift towards sustainable consumption provides a strong incentive for companies to adopt DPPs, as failure to do so could result in reputational damage and loss of market share (Nielsen, 2020).

Technological Factors

The successful implementation of DPPs relies heavily on technological advancements. While blockchain technology is central to ensuring the security and transparency of the data contained in DPPs, other technologies also play crucial roles. For instance, QR codes and RFID chips are essential for linking physical products to their digital passports. QR codes, which can be easily scanned by consumers using smartphones, provide instant access to a product's DPP, offering detailed information about its lifecycle and sustainability credentials. RFID chips, on the other hand, are particularly useful in supply chains for tracking products in real time, ensuring that data in the DPP is constantly updated (World Economic Forum, 2020).

The integration of Internet of Things devices enhances the functionality of DPPs by enabling real time monitoring of products throughout their lifecycle. IoT devices can collect and transmit data on product usage, environmental conditions, and other factors that impact the product's lifecycle, feeding this information into the DPP. Additionally, Artificial Intelligence (AI) and big data analytics can be employed to analyze the vast amounts of data generated by

DPPs, helping companies optimize their supply chains and improve sustainability outcomes (SupplyChainBrain, 2025).

The combination of these technologies - blockchain, QR codes, RFID, IoT, AI, and big data analytics - creates a robust technological ecosystem that supports the implementation of DPPs. Companies must invest in these technologies and ensure they have the necessary infrastructure and expertise to manage and maintain these systems.

Environmental Factors

Environmental considerations are a primary driver for the adoption of DPPs. The global urgency to address climate change and reduce environmental impact has led to increasing regulatory pressures on companies to adopt sustainable practices. DPPs directly contribute to environmental sustainability by promoting the circular economy, enabling better resource management, and reducing waste (Contentserv, 2025).

In Europe, the focus on reducing carbon emissions, minimizing waste, and promoting the reuse and recycling of materials is a key component of the EU's environmental policy. DPPs play a crucial role in achieving these objectives by providing detailed information on the environmental impact of products, from their production to their end-of-life disposal. This transparency allows for more informed decision making by consumers and businesses, leading to more sustainable consumption and production patterns (European Environment Agency, 2022).

Companies that adopt DPPs can enhance their environmental credentials, which is increasingly important as both consumers and regulators demand greater accountability in terms of sustainability. This alignment with environmental goals not only helps companies comply with regulations but also improves their brand image and market positioning (Contentserv, 2025).

Legal Factors

Legal factors are among the most critical considerations for companies implementing DPPs, particularly given the stringent regulatory environment in the European Union. The EU is leading the charge in establishing legal frameworks that mandate the use of DPPs for certain

products, as part of its broader sustainability and circular economy goals (European Commission, 2025).

Compliance with these regulations is essential, as non-compliance can result in significant legal and financial penalties. For instance, the General Data Protection Regulation (GDPR) imposes strict requirements on how personal data is handled, and any DPP system must be designed to comply with these regulations to avoid breaches (European Union, 2018). Additionally, companies must ensure that their DPP systems are aligned with the specific requirements of the Sustainable Products Initiative, which outlines the types of data that must be included in the DPP and how it should be managed (European Commission, 2020).

The legal landscape for DPPs is complex and evolving, requiring companies to stay informed and adaptable. Ensuring compliance with both current and future regulations is not only a legal necessity but also a strategic advantage, as it positions companies as leaders in sustainability and transparency.

6.2 Business Model Canvas

In developing a Business Model Canvas for the implementation of Digital Product Passports, it's essential to consider the various components that contribute to the strategic framework (BMC, Strategyzer 2024). This analysis will help to glue together the complex interactions between different aspects of the business model, providing a comprehensive understanding.

Key Partners

The adoption of Digital Product Passports relies on a network of key partners that ensure the technical and regulatory integration of the system. Technology providers are crucial, offering the necessary blockchain infrastructure, QR and RFID technologies, and IoT devices that make DPPs functional and reliable. Additionally, collaborations with regulatory bodies and environmental organizations help ensure that the DPP systems are compliant with current laws and contribute to broader sustainability goals. Industry associations play a pivotal role in standardizing DPP practices across different sectors, facilitating uniformity and ease of adoption across market players.

Key Activities

Core activities in the deployment of DPPs involve the development and integration of robust technological solutions that handle complex data with high security and efficiency. This includes creating systems capable of integrating blockchain technology for data integrity and transparency. Stakeholder engagement is another critical activity, involving continuous interaction with manufacturers, consumers, and recyclers to foster widespread acceptance and effective utilization of DPPs. Moreover, staying compliant with evolving regulations necessitates ongoing monitoring and adaptation of business practices to meet new standards.

Key Resources

The backbone of the DPP system consists of technological infrastructure, specialized human capital and comprehensive data management functions. Technological resources include secure servers for data storage and advanced software for data processing and blockchain management. Human resources are essential, with expertise in IT, sustainability and regulatory compliance driving the development and operationalization of DPPs. Data resources comprising the information contained in each passport require careful management to ensure accuracy and availability.

Value Propositions

DPPs offer substantial value by increasing transparency in product lifecycles and supporting compliance with environmental regulations. For companies, this translates into enhanced market positioning and consumer trust as they are able to provide verifiable information about product sustainability. For consumers, DPPs offer the assurance of purchasing products that are aligned with their values on sustainability, potentially influencing purchasing decisions and fostering brand loyalty.

Customer Relationships

Building and maintaining strong relationships with customers through DPPs involve ensuring continual engagement and trust. This is achieved by providing transparent access to the DPP data, allowing consumers and other stakeholders to understand the environmental impact

and origin of products. Regular feedback mechanisms and customer support services help address any concerns and improve the system based on user input.

Channels

Effective communication channels are critical for delivering the data from DPPs to various stakeholders. Digital platforms like dedicated apps or product specific web pages serve as primary channels, offering easy access to DPP data. Additionally, integrating QR codes or RFID tags directly into product packaging allows consumers to access the DPP by simply scanning these tags with a smartphone, combining physical and digital access seamlessly.

Customer Segments

DPPs are particularly relevant to several customer segments. Environmentally conscious consumers are a primary group, as they are increasingly seeking products with verifiable sustainable attributes. Regulatory agencies are also key customers since they require compliance with environmental standards. Additionally, companies looking to enhance their sustainability practices form a significant segment, using DPPs to improve their market positioning and operational efficiency.

Cost Structure

The financial architecture of implementing DPPs encompasses both initial and ongoing costs. Upfront investments are required for developing the necessary technological infrastructure, while operational costs include maintenance, data management, and staff training. Compliance and certification processes also incur costs, as efforts to engage consumers and promote the system across markets.

Revenue Streams

Revenue models for DPPs include charging service fees to companies that use the system to manage their product data and certify their compliance with sustainability standards. Partnerships with environmental organizations and technology providers also offer potential revenue channels.

6.3 Value Chain Analysis

To conduct a Value Chain Analysis (VCA) for the implementation of Digital Product Passports, the analysis integrates insights from the literature review, data analysis, and the business cases. This VCA will delineate how each activity within the deployment of DPPs contributes to creating value and enhancing the sustainability and transparency of product life cycles (IBM, 2019).

Inbound Logistics

The effective implementation of DPPs begins with proficient inbound logistics, which involves the acquisition of high quality digital and physical resources essential for building robust DPP systems. These resources include secure and scalable blockchain technology for data integrity, advanced servers for robust data storage, and software tools for efficient data processing. These elements are fundamental, as seen in the case studies reviewed, particularly in the technological framework supporting the Battery Pass project, where specific hardware for blockchain operations was critical. Ensuring that these resources are sourced responsibly and sustainably aligns with the broader environmental goals discussed in both the literature review and data analysis sections.

The core of DPP deployment is its operations, which focus on the integration and management of data across various stakeholders' platforms. This includes the careful entry, management, and updating of product lifecycle data to ensure its accuracy and accessibility. Operations must be executed with precision, leveraging the insights from the data analysis where the importance of real time data integrity and security was emphasized. The integration of IoT and blockchain technologies, as identified in the technological factors of the PESTEL analysis, plays a crucial role in enhancing these operational capabilities.

Unlike traditional products, outbound logistics for DPPs involves the digital distribution of the product passports to manufacturers, consumers, and recyclers through user friendly interfaces. Ensuring that these platforms are secure and capable of handling significant traffic is essential, as discussed in the case studies, where the accessibility of DPP data significantly influenced stakeholder engagement and adoption rates.

Marketing strategies for DPPs focus on educating all stakeholders about the benefits and necessities of DPP adoption, aligning closely with the social factors highlighted in the PESTEL analysis. Effective communication, leveraging success stories from the literature review such as IKEA's transition towards circular economy practices, can illustrate the tangible benefits of DPPs. Engaging content that highlights the role of DPPs in enhancing product transparency and contributing to environmental sustainability can drive broader adoption.

Post deployment services are crucial in maintaining the functionality and relevance of DPP systems. This includes ongoing support, updates, and training for users to ensure they can maximize the benefits of DPPs. Feedback, as suggested in the data analysis, should be integrated to continually refine and improve the DPP offerings.

Support Activities

Technology Development:

Continuous innovation is crucial, particularly in developing more sophisticated data analysis tools and enhancing blockchain functionalities, which ensure that DPPs remain at the forefront of technological advances.

Human Resource Management:

Recruiting and retaining skilled personnel who are proficient in digital technologies and sustainability practices is vital. Training programs that are regularly updated to reflect the latest technological and regulatory changes will support the sustained effectiveness of the DPP system.

Infrastructure Management:

Managing the underlying infrastructure effectively, from IT systems to legal and financial services, ensures that DPP operations are seamless and compliant with global standards.

Procurement:

Strategic procurement policies that emphasize sustainability can reinforce the environmental goals of DPPs, ensuring that all purchased goods and services align with the broader objectives of reducing the environmental footprint.

6.4 Diffusion of Innovation Theory

In synthesizing the findings from the PESTEL analysis, Business Model Canvas, and Value Chain Analysis with Rogers' Diffusion of Innovation theory, this section aims to provide a comprehensive view of how Digital Product Passports can be effectively implemented and adopted across various sectors within the European market.

Rogers' Diffusion of Innovation theory offers a framework for understanding the mechanisms behind the adoption of new technologies like Digital Product Passports. By classifying potential adopters into distinct categories - Innovators, Early Adopters, Early Majority, Late Majority, and Laggards - the theory helps to predict and influence the adoption patterns of DPPs, which is crucial for planning effective introduction and scaling strategies (Rogers, E. M. 1983).

Innovators are those who are eager to adopt new technologies early in their introduction. These are typically entities that have been highlighted in our PESTEL analysis as benefiting from regulatory foresight, such as companies in sectors heavily impacted by the European Green Deal and new sustainability regulations. They are willing to bear higher risks to gain a first mover advantage. Following them, the Early Adopters often have great influence in their respective industries and can serve as opinion leaders, helping to push the technology into the mainstream. These groups are crucial in the Business Model Canvas, particularly in establishing key partnerships and developing initial market strategies.

The Early Majority are more deliberate and cautious but will adopt the technology once it has been proven by the earlier groups. Their adoption is essential for achieving significant market penetration and was emphasized in the Value Chain Analysis where operational efficiencies and streamlined logistics can demonstrate the practical benefits of DPPs. The Late Majority, on the other hand, may be skeptical and would only adopt due to economic necessity or

increased peer pressure. They require more evidence and reassurance, which can be addressed by reinforcing the value propositions and customer relationships identified in the BMC.

Laggards are the last to adopt an innovation. They typically have an aversion to change and may only adopt the new technology when all traditional alternatives are no longer available. Strategies for engaging this group involve increased marketing efforts and possibly leveraging policy mandates to drive adoption, a factor detailed in the regulatory compliance segment of our PESTEL analysis.

Integrating Rogers' Diffusion of Innovation theory into the practical deployment of Digital Product Passports facilitates a nuanced understanding of how different stakeholder groups may react to this technological advancement. As we delve into this integration, the focus remains on linking theoretical concepts to real world application, ensuring a seamless transition from abstract principles to actionable strategies.

The technological sophistication inherent in DPPs, especially the employment of blockchain and IoT technologies, resonates well with Innovators and Early Adopters. These groups are naturally inclined toward new technologies and can navigate the complexities associated with advanced systems. Their adoption is crucial not only because it begins the technology's lifecycle but also because their endorsement serves as a signal to subsequent groups about the technology's viability and effectiveness. This early adoption phase is critical, as it sets the groundwork for broader acceptance and provides the first real world test cases that demonstrate the technology's potential benefits and drawbacks.

As the technology progresses to the Early and Late Majority, the focus shifts towards demonstrating the technology’s practical benefits, such as operational efficiencies and compliance with regulatory standards, which were prominently featured in the Value Chain Analysis. These groups require tangible evidence of the technology's effectiveness and are less swayed by the novelty factor that appeals to earlier adopters. Therefore, strategies to engage these groups often involve more straightforward demonstrations of how DPPs can streamline operations, reduce costs, and enhance compliance with environmental

regulations. This practical demonstration helps in reducing the perceived risk associated with the adoption of new technologies.

For the Late Majority and Laggards, the challenge intensifies as these groups are typically skeptical and resistant to change. They often adopt new technologies only under considerable economic pressure or due to evolving industry standards that render old methods obsolete. Here, the combined insights from the Business Model Canvas and PESTEL analysis become valuable. Highlighting the regulatory mandates and potential economic incentives can encourage adoption among these groups. For instance, illustrating how non-compliance with sustainability regulations might lead to penalties or lost market opportunities can create a compelling case for the adoption of DPPs.

The cultural and social shifts towards sustainability, as discussed in the Social Factors of the PESTEL analysis, play a significant role in the broader acceptance of DPPs. As consumer preferences evolve to favor more sustainable and transparent products, organizations are motivated to align their operations with these values. This alignment is crucial not just for attracting consumers but also for building a brand image that resonates with the public's increasing environmental consciousness.

6.5 Sub Conclusion

The Strategic Analysis concludes with insights into the architectural integration of Digital Product Passports in aligning with sustainability goals and regulatory frameworks. The use of models such as PESTEL, Business Model Canvas, and Value Chain Analysis has been essential in assessing the external, operational, and strategic dimensions affecting DPP implementation. These frameworks have provided a comprehensive understanding of the environmental, technological, economic, and social drivers that inform the strategic deployment of DPPs. They are critical in mapping out the interaction between DPPs and market dynamics, highlighting the necessity for a system architecture that supports transparency, compliance, and stakeholder engagement. This structured analysis not only aids in visualizing the practical deployment of DPPs but also sets the foundation for the subsequent design of a blockchain-based system, ensuring that all aspects are aligned with long term sustainability and efficiency goals.

Rogers' Diffusion of Innovation theory has been applied to understand and strategize the adoption across European markets, especially as DPPs will soon become mandatory under EU regulations. This theory helps define how different stakeholders, ranging from early adopters to laggards, will interact with new technology. The strategic implementation of DPPs leveraging this model aims to secure competitive advantages by enhancing transparency and enabling more informed consumer choices.

7. Design of Architecture

A foundational component in transforming product lifecycle management through enhanced transparency and accountability, is the architectural design of a digital product passport system. The focus is to construct an architecture that not only aligns with current regulatory frameworks but also seamlessly integrates emerging technologies, setting a robust groundwork for scalability and adaptability.

While the GS1 Digital Product Passport Architecture (GS1, 2022) provides an example of a model that aligns with current best practices, the goal is to extend beyond this. The aim is to develop a system architecture that not only incorporates established best practices but also introduces mechanisms to support the future integration of blockchain technology. This approach ensures that the proposed system is not only up-to-date to current standards but is proactively designed to utilize the benefits of blockchain, including enhanced data security, immutability, and decentralized access, which are critical for digital product passports.

Outline statement

GS1 in Europe supports an architecture for EU Digital Product Passports that:

1. is based on the identity of the product, which is persistent, not on identity of the data service or passport;
2. gives maximum flexibility and future-proofing to economic operators and regulators by providing machine-readable data;
3. emphasises the potential business and marketing benefits of creating a Digital Product Passport and increases efficiency by minimising the effort needed to create them;
4. is decentralised so that although all stakeholders are identified and connected, with the physical product itself as the starting point, there is no central point of failure for the data infrastructure and therefore no vendor-locked service;
5. defines the role of an archive/notary as a body that can monitor compliance and act as a repository of record;
6. is based on open standards, as developed at GS1 and elsewhere and ensures interoperability;
7. is ready to be enhanced with new technologies that add proofs of veracity.

(GS1, 2022)

The GS1 Digital Product Passport architecture is a framework designed to enhance product traceability and sustainability across the supply chain (GS1, 2022). Central to this architecture

is the concept of product identity, which remains consistent throughout the product's life cycle rather than being tied to a data service or a singular passport. This approach ensures flexibility and future proofing for businesses and regulators alike.

The architecture is decentralized, which means that no single point of failure can compromise the integrity of the data infrastructure (GS1, 2022). This design choice not only enhances system resilience but also avoids vendor lock in, ensuring that all stakeholders can rely on universally accessible and reliable data.

Another key principle is the architecture's reliance on open standards, like those developed by GS1, which guarantee that the system is interoperable across different platforms and industries. By complying to these standards, the DPP can integrate seamlessly with existing systems, promoting efficiency and reducing the effort needed to create and maintain digital passports.

The need to develop a DPP system that incorporates Blockchain Technology arises from the imperative to manage product data transparently while ensuring the confidentiality and integrity of that data across different stakeholders. Drawing from the analysis conducted in earlier chapters, this section outlines the architectural principles essential for such a system.

From the literature review, it's obvious that privacy concerns are critical among stakeholders. Implementing 'Privacy by Design' as an architectural principle ensures that privacy is not an afterthought but is integrated into every layer of the system architecture. Blockchain technology enhances this approach through its inherent capabilities for data encryption and access control mechanisms that allow data to be shared on a need to know basis, ensuring that sensitive information is kept from unauthorized access while maintaining the necessary transparency for legitimate stakeholders.

The case studies highlighted the importance of decentralized data management in enhancing data integrity and reducing vulnerabilities associated with centralized data storage systems. Blockchain's decentralized nature ensures that data is not stored in a single location, removing the risks of data breaches and loss. Each node in the blockchain network holds a copy of the ledger, creating a robust framework for data recovery and continuity that supports regulatory compliance and operational resilience.

One critical challenge identified in the data analysis of the three case studies is the lack of interoperability among different DPP systems, which can delay the seamless exchange of information across the supply chain. Designing with interoperability in mind involves adopting standardized data formats and open APIs that facilitate data sharing and system integration.

Transparency is crucial for regulatory compliance and stakeholder trust, as demonstrated in the analysis chapters. Blockchain provides an audit trail of all transactions, which are verifiable by all parties yet secure against unauthorized alterations. Smart contracts play a big role here, automating agreements and ensuring that each transaction complies to predefined rules and regulations. This capability not only enhances transparency but also ensures that the system remains compliant with legal standards and industry best practices.

Feedback from the case studies underlines the need for a system architecture that is both modular and scalable. This allows the DPP system to scale in response to new technological advancements or changes in regulatory requirements without requiring a complete system overhaul. A modular architecture enables individual components of the DPP system to be updated independently, while scalability ensures that the system can handle growing amounts of data and an increasing number of users without degradation in performance.

Developing a blockchain-based Digital Product Passport system, a detailed overview of the architectural layers is necessary (IBM, 2024). These layers facilitate the structured implementation of the system, ensuring that each component functions optimally and in harmony. The layers are; the presentation layer, application layer, and data layer.

The presentation layer serves as the interface between the end users and the DPP system. It is designed to provide an intuitive and user friendly experience that accommodates the needs of diverse stakeholders, including manufacturers, regulators, and consumers. As discussed in the "Stakeholder Engagement" section of the data analysis chapter, the interface design is crucial for ensuring broad adoption and effective use of the system. This layer includes customizable dashboards, real time reporting tools, and mobile applications that allow users to access and interact with product passport data easily.

Emphasizing usability, the presentation layer incorporates feedback from user experience tests highlighted in the case studies. These interfaces are designed to be accessible, providing

clear, concise information that can be understood without technical expertise. For example, a consumer could scan a QR code on a product to view its entire lifecycle, leveraging blockchain's transparency to provide trustworthy and verifiable information directly to the consumer.

The application layer contains the business processes necessary to manage the DPPs effectively. It includes the deployment of smart contracts on the blockchain, which automate various aspects of the passport management, such as data validation, updates throughout the product's lifecycle, and compliance checks against sustainability standards. As mentioned in the "literature review" section, these smart contracts are crucial for maintaining the integrity and trustworthiness of the DPP system, ensuring that all transactions and data entries are consistent with predefined rules and regulations.

This layer also handles the integration with existing systems, which is essential for interoperability and data exchange. Using APIs, the DPP system can connect to relevant platforms to synchronize data across different operational areas and enhance efficiencies. The need for robust integration strategies was a significant finding from the literature review, emphasizing the importance of seamless connectivity in modern digital infrastructure.

The data layer of a Digital Product Passport system serves as the foundation where all essential product information is securely stored and managed. Think of it as the extensive library of a product's life story, from its birth in manufacturing to its various stages of use, and finally to its recycling or disposal. This layer is crucial because it holds the key details that allow various stakeholders, like manufacturers, regulators, and consumers, to access trustworthy information about products.

One of the central challenges in developing a blockchain-based Digital Product Passport system is balancing the need for transparency with the need to protect sensitive data. A DPP system requires data sharing among stakeholders, including manufacturers, regulators, suppliers, and consumers. Each of these stakeholders has different access needs, ranging from full visibility into the product's lifecycle to limited, specific information.

For internal stakeholders, such as manufacturers and suppliers, the need for detailed transparency is everything. These stakeholders must track the product lifecycle from the

sourcing of raw materials to end-of-life disposal. Through the use of permissioned access, internal stakeholders can be granted different levels of visibility based on their role and involvement in the supply chain. A manufacturer might have full access to all data, while a supplier may only need access to specific segments such as sourcing information.

For consumers, transparency is necessary in verifying sustainability claims and understanding the environmental impact of the products they purchase. Consumers today are increasingly demanding more detailed product information, such as the carbon emissions generated during production or the product's recyclability. By allowing public access to this data through applications, such as mobile apps or web portals, consumers can scan a QR code on a product to view its entire lifecycle. This transparency builds trust and ensures that the company is complying with sustainability regulations while also allowing consumers to make informed purchasing decisions.

7.1 Sub Conclusion

The design of a blockchain-based Digital Product Passport system centers around key principles that ensure the system balances data privacy with the need for transparency. These principles - privacy by design, scalability, modularity, and interoperability - are everything for a DPP system to function effectively across various industries and meet regulatory demands.

A core component of the architectural design is ensuring the privacy of sensitive product data, particularly for internal stakeholders like manufacturers, while maintaining transparency for consumers and regulators. Another significant aspect of the architecture is its modularity and scalability. This modular approach ensures that the DPP system can grow and adapt to future technological advancements. Scalability ensures that as more products and stakeholders engage with the system, performance remains consistent without bottlenecks or high costs.

interoperability, the ability to integrate seamlessly with other systems and platforms across global supply chains. This is essential for maintaining efficiency and ensuring that product data can be exchanged reliably between different stakeholders. The use of open standards

and APIs allows the DPP system to connect with other databases and systems, facilitating cross-industry communication.

The Literature Review played a big role in defining the components and functions of DPPs and exploring how blockchain technology could enhance transparency and data integrity. This chapter provided the theoretical foundation for integrating blockchain into DPPs, emphasizing the benefits of decentralized data management and the need for privacy and security in handling product data and explored industry standards such as the GS1 framework.

The Case Studies offered insights into the implementation of DPP systems across different industries, such as CIRPASS, IKEA and The Battery Pass case study. These case studies highlighted practical challenges, including interoperability issues and the need for modular systems that can be adapted to different regulatory environments

The Strategic Analysis used tools like the Business Model Canvas and PESTEL analysis to identify the economic, social, and technological drivers behind the adoption of DPP systems. This chapter's findings were the importance of scalability and stakeholder trust, the need for a blockchain-based system that can handle growing amounts of data while maintaining integrity and transparency. The analysis also pointed to the economic benefits of reducing inefficiencies and waste through better product lifecycle management, which was integrated into the architectural design.

8. Future Work / Future Predictions

In the coming years, the focus on refining Digital Product Passport frameworks is expected to intensify, targeting key areas such as interoperability enhancement across various sectors and the augmentation of security measures and data transaction efficiencies. These developments aim to support the expansion of DPP capabilities to incorporate comprehensive environmental impact data while ensuring systems can scale to manage extensive data across diverse product groups and global supply chains.

The evolution of DPP regulations will necessitate ongoing adaptations as the regulatory landscape progresses in response to emerging sustainability challenges and deeper understandings of DPP impacts. This dynamic regulatory environment will compel both corporations and regulatory bodies to maintain agility, continuously updating practices to integrate new knowledge and technological advancements.

Looking ahead, the initial implementation focus on sectors with high environmental impacts - such as electronics, textiles, and batteries - would be expected to broaden, encompassing a wider array of industries. This expansion will demand the creation of tailored industry specific guidelines that not only address unique sectoral challenges but also harness opportunities to enhance circularity and sustainability within those domains.

It will be fascinating to revisit the topic of Digital Product Passports after the mandatory implementation period across various industries. This future investigation will provide an opportunity to assess how well the initial expectations and theoretical frameworks align with real world outcomes. The comparison between the anticipated challenges and the actual successes or setbacks encountered during implementation will offer valuable insights into the effectiveness of the strategies employed. It will also help identify any gaps that have emerged, revealing potential areas for improvement or innovation within the DPP framework.

As the system becomes more entrenched within Europe, it would be expected to expand beyond. Europe, under the European Green Deal and Circular Economy Action Plan, is at the forefront of regulatory efforts to promote sustainability, leading to the mandatory implementation of DPPs for various products.

9. Discussion

The potential impact of Digital Product Passports is substantial, particularly in advancing sustainability objectives and strengthening circular economy practices. As outlined in section 4.1 on CIRPASS, standardization efforts aim to create a harmonized framework that enables efficient data sharing, lifecycle tracking, and compliance with regulatory demands. Theoretically, this transparency should empower consumers, enhance corporate accountability, and provide regulators with an effective tool for monitoring compliance to environmental policies. However, the full realization of these benefits remains contingent on multiple factors, including technological feasibility, regulatory enforcement, and industry adoption.

The transformative potential of DPPs lies in their ability to restructure industries by enabling comprehensive traceability, facilitating material reuse and waste reduction, and enhancing product lifecycle transparency. As demonstrated in the IKEA case study, corporate engagement with DPPs can align sustainability goals with business operations, creating long term economic and reputational benefits. By integrating DPPs into their supply chain, IKEA would seeks to optimize resource use and strengthen product lifecycle accountability. However, as noted in the PESTEL analysis, regulatory and economic factors may pose significant challenges, particularly in terms of implementation costs, supply chain adjustments, and potential price increases for consumers. The question remains whether industries will prioritize long term sustainability benefits over short term economic considerations when deciding whether to invest in DPP systems.

Despite the advantages outlined in the section on Battery Pass, one of the primary obstacles to DPP adoption is widespread industry integration. The success of these systems depends on companies' willingness to invest in necessary infrastructure, upgrade existing supply chain management technologies, and comply with new data sharing and security protocols. The strategic analysis highlights how businesses could face the challenge of balancing compliance with financial feasibility. While blockchain and decentralized data storage offer security and trustworthiness, as discussed in the section Blockchain as an Enabler of DPPs, their integration demands substantial upfront investment. For companies operating on tight profit margins or

in highly competitive markets, the cost of compliance could serve as a disincentive, leading to slow adoption rates.

Another critical issue raised in the value chain analysis, is the interplay between sustainability mandates and corporate profitability. While companies adopting DPPs could benefit from increased consumer trust and regulatory alignment, the transition period may present significant financial strain, particularly for small and medium sized businesses This aligns with findings in the literature review section on Privacy and Security in DPPs, where concerns regarding data confidentiality, cybersecurity risks, and legal accountability were identified as major barriers. If businesses fear exposing proprietary information or are uncertain about how data governance will be managed, their willingness to participate in DPP adoption could be compromised.

A further concern that emerged from the comparative analysis of case studies, is whether DPPs will effectively bridge the gap between regulatory frameworks and real world application. The CIRPASS initiative provides top down standardization, but it remains unclear whether companies across industries will adopt a uniform data model or whether fragmentation in reporting and compliance will create inefficiencies.

From an economic standpoint, the PESTEL analysis raises concerns about the impact of DPP adoption on product pricing. Companies required to implement these systems may pass on costs to consumers, raising ethical and economic questions about affordability and accessibility. If DPPs become a mandatory component of sustainable product design, will consumers bear the financial burden of compliance driven transparency?

A broader discussion is warranted on the long term strategic value of DPPs beyond regulatory compliance. Companies that embrace proactive digital traceability, rather than treating DPPs as a bureaucratic obligation, may unlock new business opportunities, enhanced brand reputation, and competitive differentiation. The insights from IKEA's corporate strategy suggest that forward thinking companies can leverage DPPs to reinforce consumer trust, drive circular innovation, and strengthen environmental commitments. However, if companies fail to see the strategic advantages, DPP adoption could remain a minimal compliance exercise rather than a tool for transformational change in supply chains.

This discussion reveals both positivity and caution in assessing the impact of DPPs. While the potential to redefine product lifecycle management and sustainability reporting is significant, real world implementation hangs on economic feasibility, industry engagement, and technological preparedness. The findings from the case studies, the literature review, and the strategic analysis collectively shows that DPPs represent a powerful mechanism for sustainability, yet their success will depend on how well regulatory structures, business incentives, and technological innovations align in the coming years. The next chapter will build upon these insights to propose a design framework that addresses the key barriers identified in this discussion while leveraging the strengths of existing case studies to develop an adaptable, scalable, and compliant DPP model.

10. Conclusion

This thesis has examined how a blockchain-based Digital Product Passport can balance data privacy and transparency to support circularity and sustainability. Through a combination of literature review, case studies, and analytical frameworks, this study has developed a comprehensive understanding of the potential, challenges, and implications of DPPs for businesses, regulators, and consumers. Based on these findings, it is possible to answer both the specific research questions and the overarching problem statement.

The first research question focused on identifying the key components and functions of a DPP and how they contribute to sustainability and circularity. As highlighted in the literature review and case studies, a DPP contains detailed information on a product's lifecycle, including raw material extraction, production processes, distribution, usage, and end-of-life management. By enabling digital tracking and registration of materials and components, DPPs enhance transparency, which facilitates more efficient resource utilization. This benefits companies by optimizing reuse and reducing waste while empowering consumers to make more informed purchasing decisions based on sustainability data. Additionally, DPP systems support regulatory compliance and allow authorities to monitor companies' adherence to environmental and circular economy standards. The CIRPASS project demonstrates how standardization efforts at the European level aim to ensure cross-sectoral consistency in data exchange, while the IKEA case with the implementation of digital traceability showcases the business value of DPPs in optimizing resource efficiency and strengthening consumer trust. The Battery Pass initiative, on the other hand, highlights the importance of lifecycle transparency in industries with stringent sustainability requirements, particularly in ensuring responsible sourcing and material recovery in battery production. Across these cases, it is evident that DPPs play a pivotal role in supporting circular economy principles by providing actionable, verifiable sustainability data throughout the product lifecycle.

The second research question explored how blockchain technology can be integrated into DPPs to ensure secure data management and interoperability across complex supply chains. As discussed in the blockchain section and case studies, blockchain provides a decentralized and immutable database where product data can be securely stored, preventing unauthorized alterations. Technologies such as smart contracts and encryption enable

selective access to data, ensuring that sensitive business information - such as supplier relationships and production methods—remains protected while making relevant product data accessible to consumers and regulators. A key insight from the analysis is the need for interoperability between different systems and platforms, as supply chains often span multiple countries and technological infrastructures. By using standardized protocols, blockchain-based DPPs can ensure that data is securely exchanged across systems without compromising security or privacy. The Battery Pass case study exemplifies how blockchain ensures regulatory compliance by securely logging each stage of a battery's lifecycle, from production to recycling, while also enabling seamless cross border data exchange. However, the findings also highlight challenges such as the need for interoperability between different blockchain protocols and ensuring that blockchain-based systems align with existing enterprise IT infrastructures. The analysis underscores that while blockchain offers a robust solution for securing DPP data, its successful implementation depends on standardized frameworks for cross-industry adoption and efficient integration with broader digital ecosystems.

The third research question examined how external market, and regulatory factors influence the adoption and strategic implementation of blockchain-based DPPs. The PESTEL analysis and Business Model Canvas have highlighted how legislation, economic incentives, and technological advancements drive the development of DPP systems. European regulatory frameworks, including the Ecodesign for Sustainable Products Regulation (ESPR) and the EU Data Act, create political pressure for companies to implement DPPs to ensure compliance with sustainability, traceability, and resource efficiency requirements. At the same time, the strategic analysis suggests that companies can gain competitive advantages by adopting DPPs early, as they can strengthen brand value, secure market access, and mitigate risks associated with non-compliance. However, economic barriers to implementation persist, particularly for small and medium-sized businesses that may struggle to absorb the initial investment costs. The CIRPASS project illustrates the importance of regulatory driven standardization in accelerating DPP adoption, while the Battery Pass initiative underscores how industry specific policies are shaping DPP deployment in high risk sectors. Moreover, the analysis of the IKEA case, business strategy suggests that while leading multinational corporations may leverage

DPPs as a competitive advantage, the widespread adoption of such systems requires clear incentives, industry wide collaboration, and supportive regulatory frameworks.

The fourth research question addressed the architectural design principles necessary for developing a blockchain-based DPP that balances data privacy with the need for transparency. As outlined in the architecture chapter, privacy-by-design is a crucial element in DPP development, ensuring that blockchain-based solutions integrate access control, encryption, and selective disclosure to protect business critical data while allowing consumers to access environmental impact information. Modularity and scalability are also essential design principles that enable DPP systems to adapt to changing regulatory requirements and technological advancements without needing to be completely restructured. Additionally, the analysis emphasizes the necessity of standardized data models to ensure that DPPs function seamlessly across industries and geographic regions. The findings from the Battery Pass project illustrate how selective transparency can be implemented to ensure that companies disclose only the necessary environmental and regulatory compliance data while safeguarding proprietary information. However, challenges remain in finding the optimal balance between openness and confidentiality, particularly in ensuring that DPP data does not conflict with GDPR and other global privacy regulations. The strategic analysis of blockchain-based DPPs suggests that future architectural frameworks should prioritize scalability, modularity, and interoperability to accommodate evolving regulatory demands and industry needs.

With these findings in mind, the overarching problem formulation - "How can a blockchain-based Digital Product Passport balance data privacy and transparency to support circularity and sustainability?" - can be answered. By leveraging blockchain technology, DPPs can ensure data integrity, immutability, and selective access control, creating a balanced approach where business secrets remain protected while maintaining transparency for regulators and consumers. Additionally, blockchain enhances interoperability, which is crucial for widespread adoption in multi stakeholder supply chains. At the same time, the analysis shows that successful implementation depends on external factors such as regulatory pressures, economic incentives, and technological readiness. For DPPs to reach their full potential, a strong alignment between technological solutions, regulatory requirements, and industry collaboration is necessary.

This thesis supports the view that blockchain-based DPPs can be a powerful driver of circularity and sustainability. However, their success will depend on how they are designed, regulated, and adopted in practice. While CIRPASS emphasizes the importance of standardization, the IKEA case illustrates corporate level implementation strategies, and Battery Pass demonstrates sector specific compliance solutions, their combined insights highlight the multifaceted nature of DPP adoption and the necessity of aligning technological innovation with policy driven mandates.

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