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Vorarlberg University
of Applied Sciences

Distributed Ledger Technology in the Circular Economy

Enable Traceability and Transparency of Recyclable Products with a Digital Product Passport Platform

Master's Thesis
Submitted in Fulfillment of the Degree

Master of Science in Engineering (MSc)

Vorarlberg University of Applied Sciences
Computer Science

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Dornbirn, July 2023

Abstract

Lack of transparency and traceability of products and their raw materials means that most products can only be thrown away or not properly recycled due to a lack of relevant data. This conflicts with the circular economy principles, which are demanded by several initiatives, including the European Union.

The aim of this master thesis is to analyze this conflict and to propose a technical solution based on Distributed Ledger Technology that enables transparency and traceability of products and their materials. Therefore, the thesis addresses two central research questions:

1. How can traceability and transparency be enabled by integrating a DLT solution?

2. How would a prototype with the integration of smart contracts and DLT look like?

To answer these questions, a blockchain solution is implemented using *Hyperledger Fabric*. The solution uses the immutability and decentralized nature of DLT to record and track the movement of products and their materials throughout their life cycle in the Circular Economy. Furthermore, with private data collections, confidentiality, and privacy are granted while ensuring transparency. The thesis contributes to the Circular Economy field by exploring the principles, models, and challenges of the Circular Economy and the circularity goals of a Digital Product Passport to develop a suitable technical solution. The chosen blockchain framework, *Hyperledger Fabric*, is presented, and its key components and features are highlighted. The thesis also delves into the design decisions and considerations behind the Digital Product Passport platform, explaining the architecture and transaction flow together with the prototype implementation and demonstration to showcase the functionality of the solution. Results and analysis provide insights into the challenges of the Circular Economy, sustainable resource management, and the Digital Product Passport, resulting in recommendations for future improvements and enhancements.

Overall, this thesis offers a practical solution utilizing DLT to enable transparency and traceability in the Circular Economy, contributing to the realization of sustainable and efficient resource management practices to ultimately contribute to the set Circular Economy initiatives.

Kurzreferat

Mangelnde Transparenz und Nachverfolgbarkeit von Daten über Produkte inklusive deren Rohstoffen resultiert oft darin, dass Produkte weggeworfen oder nicht richtig recycelt werden können. Dies steht in einem Konflikt zu den Zielen der Kreislaufwirtschaft, die von immer mehr Initiativen, sowie der Europäischen Union, gefordert werden.

Die vorliegende Arbeit analysiert diesen Konflikt und bietet eine technische Lösung auf Basis der Distributed Ledger Technology (DLT), die Transparenz und Nachverfolgbarkeit von Produkten und deren Materialien ermöglicht. Die Arbeit befasst sich mit zwei zentralen Forschungsfragen:

1. Wie können Nachverfolgbarkeit und Transparenz durch die Integration einer DLT-Lösung ermöglicht werden?
2. Wie sieht ein Prototyp mit der Integration von Smart Contracts und DLT aus?

Um diese Fragen zu beantworten, wird eine Blockchain-Lösung mit *Hyperledger Fabric* implementiert. Die Lösung nutzt die Unveränderlichkeit und den dezentralen Charakter der DLT, um die Bewegung von Produkten und ihren Materialien während ihres gesamten Lebenszyklus in der Kreislaufwirtschaft aufzuzeichnen und zu verfolgen. Vertraulichkeit und Datenschutz wird dabei mit privaten Datensammlungen sichergestellt, ohne auf die erforderliche Transparenz verzichten zu müssen. Die Prinzipien, Modelle und Herausforderungen der Kreislaufwirtschaft und die Ziele der Kreislaufwirtschaft eines digitalen Produktpasses werden untersucht, um eine geeignete technische Lösung zu entwickeln. Das gewählte Blockchain-Framework, *Hyperledger Fabric*, wird vorgestellt und seine wichtigsten Komponenten und Funktionen werden hervorgehoben. Die Arbeit geht auch auf die Designentscheidungen und Überlegungen ein, die hinter der Plattform des Digitalen Produktpasses stehen, und erläutert die Architektur und den Transaktionsfluss zusammen mit der prototypischen Implementierung und Demonstration. Die Ergebnisse und Analysen geben Einblicke in die Herausforderungen der Kreislaufwirtschaft, des nachhaltigen Ressourcenmanagements und des Digitalen Produktpasses, was zu Empfehlungen für zukünftige Verbesserungen und Erweiterungen führt.

Insgesamt bietet diese Arbeit eine praktische Lösung, die DLT nutzt, um Transparenz und Rückverfolgbarkeit in der Kreislaufwirtschaft zu ermöglichen und so zur Verwirklichung eines nachhaltigen und effizienten Ressourcenmanagements beizutragen.

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List of Abbreviations

API Application Programming Interface

CA Certificate Authority

CFT Crash Fault Tolerant

CLI Commando Line Interface

DLT Distributed Ledger Technology

DPP Digital Product Passport

EC European Commission

ERP Enterprise-Resource-Planning

IP Intellectual Property

JIDEP Joint Industrial Data Exchange Platform

JSON JavaScript Object Notation

MSP Membership Service Provider

NFC Near Field Communication

PKI Public Key Infrastructure

QR Quick Response

RFID Radio Frequency Identification

SDK Software Development Kit

SRM Sustainable Resource Management

1 Introduction

In the last couple of years, initiatives like the *European Green Deal* have been imposed on companies to positively impact the sustainability status of products. This means that a majority of products are often declared sustainable. In fact, the extent of the products' sustainability is often questionable, as such data is usually concealed or not made public. One part of sustainability is the reduction of waste through recycling, which has given rise to the concept of the Circular Economy. The Circular Economy is a regenerative economic system aiming to minimize waste and maximize resource efficiency by promoting the continual use and recycling of materials. However, the Circular Economy is not just about recycling, but likewise about keeping track of the entire system and product life cycle.

The European Union has set itself the goal of implementing the *new Circular Economy action plan (CEAP)* as part of the *European Green Deal*. This has now given rise to projects such as the Joint Industrial Data Exchange Platform (JIDEP). JIDEP aims to provide a data exchange platform that connects independent industrial data in a cooperation pipeline. Additionally, the goal is to preserve resources and materials to utilize them as long, as often, and to produce as little waste as possible. Furthermore, the re-usability of data in the industry and the facilitation of the development of data values is an important goal. Built-in tools should be able to unlock the value of data, which can then be used to provide and develop sustainable materials, products, services, solutions, and technologies.

JIDEP is also an optimization continuum that covers the entire product life cycle and aims to implement closed-loop systems at the technological and regulatory levels. Furthermore, JIDEP collects industry data and creates sustainability, resilience, and Circular Economy artifacts for its participants. The implementation of such a platform requires a technical solution that allows different actors to participate in a Circular Economy and also facilitates the achievement of the stated goals of a Circular Economy.

The question arises whether the implementation of such a platform with the usual technical means and conventional databases is sufficient, or whether new technologies are better suited to achieve the goals.

> Problems can never be solved with the same mindset that created them. - Albert Einstein.

JIDEP is a project in which several universities and universities of applied sciences are involved, but this master's thesis is not directly related to JIDEP. However, the master thesis was motivated by the idea of researching a technical solution to the same goals of JIDEP and the Circular Economy. This ultimately has the potential to support these initiatives with new ideas and solutions.

The lack of traceability, transparency, and monetary incentives in the recycling process has led to collective negligence. The use of Distributed Ledger Technology (DLT) could be a possible solution for these problems. Therefore, DLT can be seen as a glimmer of hope for achieving the goals of a Circular Economy. Consequently, this work deals with the possible development of a platform supported by DLT to develop a general solution with the same goals as the JIDEP project. This is exactly the area in which this master's thesis researches and evaluates the potential, limitations, and technical solutions to support the goals of the Circular Economy.

1.1 Research Questions

The main objective of this master thesis is to explore the potential of blockchain technology in supporting a Circular Economy platform, especially in terms of traceability and transparency. To achieve this, the following research questions, which serve as the fundamental issues of this thesis, have been set up:

1. **How can traceability and transparency of materials used in products in the Circular Economy be enabled with the integration of a Distributed Ledger Technology solution?**

   Traceability and transparency are critical components of a Circular Economy platform. The integration of DLT can enable secure and transparent tracking of materials and products throughout the supply chain. This research question focuses on identifying the key components of a DLT solution, that can facilitate traceability and transparency in the Circular Economy.

2. **How might a prototype with the integration of smart contracts and Distributed Ledger Technology look like?**

   Smart contracts are contracts that automatically execute based on the predefined terms written in code, eliminating the need for intermediaries between buyers and sellers. The integration of smart contracts into a DLT solution can enable automated and secure transactions, further enhancing the effectiveness of a Circular Economy platform. This research question focuses on the architecture, design, and development of a prototype with the integration of smart contracts and DLT to demonstrate the potential of this technology in supporting Sustainable Resource Managements (SRMs).

Overall, the research questions in this master thesis aim to explore the potential of blockchain technology in supporting a Circular Economy platform and to provide insights that can inform the development of future Circular Economy initiatives. By addressing these research questions, this thesis will contribute to the growing body of knowledge on the use of blockchain technology in Sustainable Resource Management and the Circular Economy.

1.2 Objectives

The main objective of this master thesis is to investigate the potential of integrating DLT into a Circular Economy platform. The thesis aims to provide insights on how DLT can enable traceability and transparency, and how to unlock data and verify the integrity of the shared data.

To achieve the major objective, it is divided into individual sub-objectives that result from the scientific questions and are dealt with in the course of this thesis.:

Literature Review

One crucial objective is the literature review. The objective is to give an overview of the current research around the Circular Economy and the principles that can be supported by DLT. Additionally, the different types of blockchain technologies and suitable methods that are valuable to the Circular Economy are researched and analyzed. Also, related work that already provides solutions in this area gets examined. Further, the literature review should also address the derived objectives from the JIDEP project. These objectives are primarily to preserve the worth of materials to be used as long as possible and produced with as little waste as possible. Additionally, the re-usability of data should be provided to facilitate the evolution of sustainable materials, products, services, and solutions. Furthermore, existing initiatives that research similar issues and solutions are evaluated, enabling areas where those solutions could be better. With this insight, a conclusion can be made on how to be better in those fields to implement a solution that achieves the goals of a Circular Economy. The literature review should build the foundation for finding adequate solutions to minimize the lack of traceability and transparency of the materials used in products in the Circular Economy. With this knowledge, the prototype can then be built using technical tools and frameworks. Therefore, the conducted literature review should give a thorough understanding of how and which technologies allow the achievement of the following objectives.

Prototype Design and Implementation

Part of this sub-objective is to design a prototype for a Circular Economy data exchange platform that is usable by different types of organizations. With the integration of smart contracts and DLT, it should demonstrate the potential of this technology in supporting Sustainable Resource Management and pursue the same goals as the JIDEP Project and the Circular Economy. The prototype shall show how a DLT solution, which can be integrated into an existing system, works to subsequently enable tamper-proof, traceable, and transparent recycling in a Circular Economy and allow participants to unlock important data securely.

Analysis of the Results

Another objective is to analyze the resulting solution, which means evaluating the effectiveness of the prototype by verifying its ability to enable traceability and transparency. Furthermore, the goal of the analysis is to check whether the objectives and challenges of the Circular Economy, the Digital Product Passport, and the research questions are achieved with the prototype. This part also includes a review of implementation limitations and recommendations for further development initiatives in the same field.

Consequently, the objective of these insights is to emphasize the development of future Circular Economy initiatives and promote the adoption of sustainable practices in industries.

1.3 Significance and Contribution of the Research

The significance of this research lies in its potential to address the challenges faced by the Circular Economy and Sustainable Resource Management. By integrating DLT into existing collaborative platforms, the traceability, and transparency of materials used in products can be enabled, positively impacting resource management, while also reducing waste. This can contribute positively to the environment and aid in the attainment of the *United Nations Sustainable Development Goals*.[1]

Furthermore, this study offers a valuable and multifaceted contribution to the field. Firstly, it provides insights into the potential of DLT in the Circular Economy, demonstrating the effectiveness of this technology in enabling traceability and transparency, and supporting Sustainable Resource Management. Secondly, this research presents a prototype solution for a Circular Economy platform by using smart contracts and DLT, providing a proof of concept that can serve as a basis for the development of further tools and applications to contribute to the Circular Economy.

Significant research has already been conducted individually on the respective topics of the Circular Economy and DLTs. For the Circular Economy, for instance, the *Towards the Circular Economy* report by the *Ellen MacArthur Foundation* highlights the advantages in terms of economics, environment, and society when adopting circular principles and gives guidelines to businesses and policymakers on how to implement circular strategies.[2]. But there are also books like *The Circular Economy Handbook* by Lacy Peter, Long Jessica, and Spindler Wesley. The book serves as a guide with concrete steps on strategies for transitioning towards a circular economy. Further, it provides an overview of how organizations can transition towards a circular economy to unlock new possibilities for competitiveness and sustainable prosperity.[3] Books on distributed ledger technology with a focus on the supply chain are very widespread. One example is *Blockchain and the Supply Chain* by Vyas Nick, which shows how to use blockchain to build solutions for the supply chain.[4] Nevertheless, only a few researches are focusing on the complementation of those areas. Therefore, a contribution about the combination of DLT and the Circular Economy possesses the capacity for future initiatives that plan to implement more sustainable product data management. In essence, this research possesses the potential to foster a future that is more sustainable and resilient.

2 State of the Art

The Circular Economy has emerged as a promising concept to address the challenges of Sustainable Resource Management and waste reduction. However, the implementation of Circular Economy initiatives requires efficient resource management, which can be facilitated by the use of technological tools and frameworks. In recent years, DLT has gained attention as a potential solution to enable more efficient resource management in the Circular Economy, especially by solving the problems of transparency and traceability.[5] This chapter provides a review of the literature on the use of DLT in the Circular Economy, suitable technologies, and the potential to address the corresponding challenges faced by Sustainable Resource Management.

2.1 Circular Economy

By definition, a Circular Economy is an industrial economy that's intention is to be restorative. Therefore, such an economy relies heavily on sustainable energy, traceability, and removal of toxic chemicals, and waste reduction through diligent design.[2] Circular Economy has emerged as a promising approach to promoting sustainable development and reducing environmental impacts. According to the European Commission, Circular Economy is a concept where waste is minimized, products and materials are reused or recycled, and environmental harm is reduced in the production and consumption of goods. The goal of the Circular Economy is to establish a self-sustaining system in which resources are utilized for extended periods, maximizing their value while minimizing the generation of waste.

The adoption of Circular Economy principles can bring numerous benefits, such as reducing resource depletion, decreasing waste generation, and mitigating climate change. Additionally, Circular Economy can create new economic opportunities, support innovation, and promote sustainable development. However, implementing Circular Economy requires a collaborative effort among stakeholders and policy-makers.[6]

2.1.1 Circular Economy Principles, Models, and Challenges

At its core, a Circular Economy is based on the five principles of *design out waste*, *build resilience through diversity*, *rely on energy from renewable sources*, *think in 'systems'*, and *waste is food.* Each principle offers a unique perspective on how to contribute to the Circular Economy, where waste is minimized, and the preservation of resources is prioritized. While the adoption of Circular Economy principles presents immense opportunities, there are also significant challenges, including the need for policy support and incentives to facilitate the transition. In this chapter, the most important principles that should be observed when developing a Circular Economy solution will be explored. Therefore, the focus will be put on principles that are most appropriate for the transparency and traceability of products and their materials within a sustainable and resilient economy.[2]

Design out waste

The *design out waste* principle follows the idea that waste results from design flaws. When designing services or products, the developer should plan it by considering how it can be recyclable or biodegradable. The principle proposes that products, services, and systems should be designed with the end of life in mind, making them recyclable or biodegradable.[2, p. 23] The principle involves the use of materials that can be easily disassembled, repaired, or reused.[3, p. 33]

The significance of this principle is that it helps to reduce waste and to save resources, potentially resulting in new ideas for innovation. For example, the design of a phone that can be easily repaired and upgraded reduces the need for new devices and decreases electronic waste. Another example is the use of reusable packaging, reducing waste from single-use packaging.

Build resilience through diversity

The principle of *build resilience through diversity* highlights the significance of diversity in ecosystems, economies, and societies.[2, p. 23] This principle suggests that diverse systems are more adaptable to changes and shocks, thus increasing their resilience and development.[7] To achieve this principle, one must leverage a range of resources, suppliers, and markets to avoid over-reliance on a single source.

The importance here lies in reducing the vulnerability of systems to disruptions while opening up new avenues for innovation. For instance, a business that sources materials from multiple suppliers instead of a single one can mitigate supply chain disruptions. Another example is the adoption of diverse crop varieties of agriculture, strengthening the ability to withstand and adapt to the effects of climate change.

Rely on energy from renewable sources

To promote the use of clean and renewable energy, the Circular Economy principle of *rely on energy from renewable sources* proposes the adoption of sources like wind energy, solar energy, hydro energy, or tidal power instead of relying on coal, oil, and gas only.[7] Furthermore, the principle also suggests implementing energy-efficient technologies to lower energy consumption.

The significance of this principle is highlighted in two critical areas. Firstly, it helps to mitigate greenhouse gas emissions, playing a significant role in addressing climate change. Secondly, it reduces the reliance on finite and polluting fossil fuels, leading to greater energy security. For example, a company that utilizes solar panels to power its operations reduces its carbon footprint, while using electric vehicles helps to reduce emissions from transportation.[2, p. 23]

Think in 'systems'

The *think in 'systems'* principle proposes using a systems thinking approach, considering the interconnections of systems and their components. The principle involves the use of a holistic approach, analyzing the whole system rather than its individual parts.[2, p. 23] Furthermore, it is also about different actors working together to continuously educate each other about materials and important information.[7]

This principle helps to identify and address the root causes of problems, rather than just treating the symptoms. Additionally, it supports collaboration and innovation. For example, a company uses a life cycle assessment approach, analyzing the environmental impacts of its products from raw materials to end-of-life.

Waste is food

Waste is food is a principle that proposes that waste from one process becomes a resource for another process, creating a closed-loop system. Therefore, products that are not used anymore, should not be treated as waste, but instead be used as part of a new cycle.[7] The principle involves the use of circular value chains, where waste is reused or recycled.

With this principle in mind, waste gets reduced and resources are saved. It also supports new inventions and results in new commercial ideas. For instance, a company that uses waste as a feedstock for the production of new products reduces the need for virgin materials.[2, p. 23]

All Circular Economy principles have to overcome key challenges in terms of adoption due to a lack of policy support and incentives. In fact, the transition to Circular Economy requires significant investments and changes in the existing economic systems, which can be challenging without proper policy frameworks and incentives. Therefore, governments and policy-makers have a decisive factor in promoting Circular Economy through policy support, regulations, and incentives.[2, p. 23]

2.1.2 Sustainable Resource Management

Sustainable Resource Management (SRM) is a critical approach to promoting sustainable development and reducing environmental impacts. SRM aims to guarantee the usage of biological resources, such as water energy, minerals, and land in a sustainable manner while minimizing waste generation and environmental harm. Sustainable Resource Management requires a comprehensive and integrated approach that addresses the ecological, social, and business dimensions.

The adoption of SRM principles can bring numerous benefits, such as reducing resource depletion, improving resource efficiency, and promoting sustainable development. Additionally, SRM can create new economic opportunities, support innovation, and promote environmental justice. However, implementing SRM requires a collaborative effort among stakeholders and policy-makers.

Sustainable Resource Management principles encompass various strategies and practices that promote sustainability in different economic sectors. The following introduces some of the key SRM principles that should also apply to the resulting outcomes of this research:

Resource efficiency

This principle emphasizes the importance of using resources more efficiently and sustainably, reducing waste generation, and promoting sustainable production and consumption. Resource efficiency fits the defined objectives of this research, as it also pursues to decrease waste and promote sustainable production and consumption by tracking the materials within products to use them again.

Life cycle thinking:

Life cycle thinking involves considering the complete product life cycle, from production to disposal, to identify opportunities for resource efficiency and litter deduction. The solution of this research should also fulfill this principle in the best possible way through transparency and traceability throughout the cycle.

Circular Economy

This principle advocates for creating closed-loop systems where waste from one system is used as a resource in another system, promoting resource efficiency and reducing waste generation. Since the solution is designed primarily for recycling companies, as well as the original manufacturers and material producers, a closed ecosystem is created that complies with the principles of the Circular Economy.

Sustainable procurement

Sustainable procurement involves incorporating environmental and social considerations in the procurement process, promoting sustainable production and consumption. This thesis aims to especially emphasize that recycled materials can be bought back via a common platform in the procurement process.

Stakeholder engagement

This principle emphasizes the importance of engaging stakeholders in the decision-making process, promoting transparency and accountability in SRM. As the research thrives to enable the best possible transparency and traceability, all stakeholders participating in the platform should have transparent access to the data to decide if the materials correspond to their requirements for sustainability.
Sustainable Resource Management has been applied in various economic sectors, such as agriculture, manufacturing, and transportation. However, the implementation of SRM requires a supportive policy framework and diverse incentives. Here, governments and policy-makers can have a crucial impact in promoting SRM management by establishing policy support, regulations, and incentives.

In conclusion, SRM offers a promising approach to promoting sustainable development, reducing environmental impacts, and creating new economic opportunities. The adoption of SRM requires a collaborative effort among stakeholders and policy-makers to overcome existing challenges and create a supportive framework for SRM. [8]

2.2 Digital Product Passport

One aspect that aligns with the objectives of the thesis is the Digital Product Passport (DPP), which is recommended by the European Commission (EC) in their *Circular Economy Action Plan*. The objective of the DPP is to function as a digital document that offers details concerning a product's environmental and social impact, along with information about its design, composition, origin, and repair history.

The EC wants to develop a standardized way of sharing product information across the supply chain, which should make it easier for businesses to take decisions about the products they want to buy or sell. Thereby, the generated information flow contributes to reducing waste, improving resource efficiency, and promoting the use of sustainable materials, supporting the objectives of this research.

In two of the ECs publications called *The EU Digital Product Passport shapes the future of value chains: What it is and how to prepare*[9] as well as in *Enabling circularity through transparency: Introducing the EU Digital Product Passport*[10] the EC defines some elements of the DPP that are not completely defined yet and still have to be answered. The EC defined and divided the topics into different categories together with the corresponding question that has to be answered:

Scope:

- **Product groups**: "Which industries/product groups should be prioritized and why?"
- **Company size**: "Should requirements differ by company size?"
- **Application level**: "What level should DPPs be applied at?"

Tech:

- **Data storage**: "How and by whom should data be stored?"
- **Data carrier**: "What data carrier(s) should be used?"
- **Access/security**: "How should access to the data be allowed?"

Data:

- **Data requirements**: "What information/data will be included in the DPP at what degree of standardization?"
- **Governance**: "Who collects and updates the data? How is the DPP data verified?"

Especially the Application level and the topics of the Tech and Data section will be emphasized for this technical thesis. As shown in Figure 2.1 on page 14 these topics are mostly undefined yet or at least not completely defined yet, which can be observed in the figure by the proportion of gray color in the *Degree of maturity in EU DPP regulation* indicator. Consequently, those points provide a strong foundation for analyzing and answering the questions of these related topics. The subsequent paragraphs provide further elaboration on the topics that are crucial for the implementation of the research prototype.

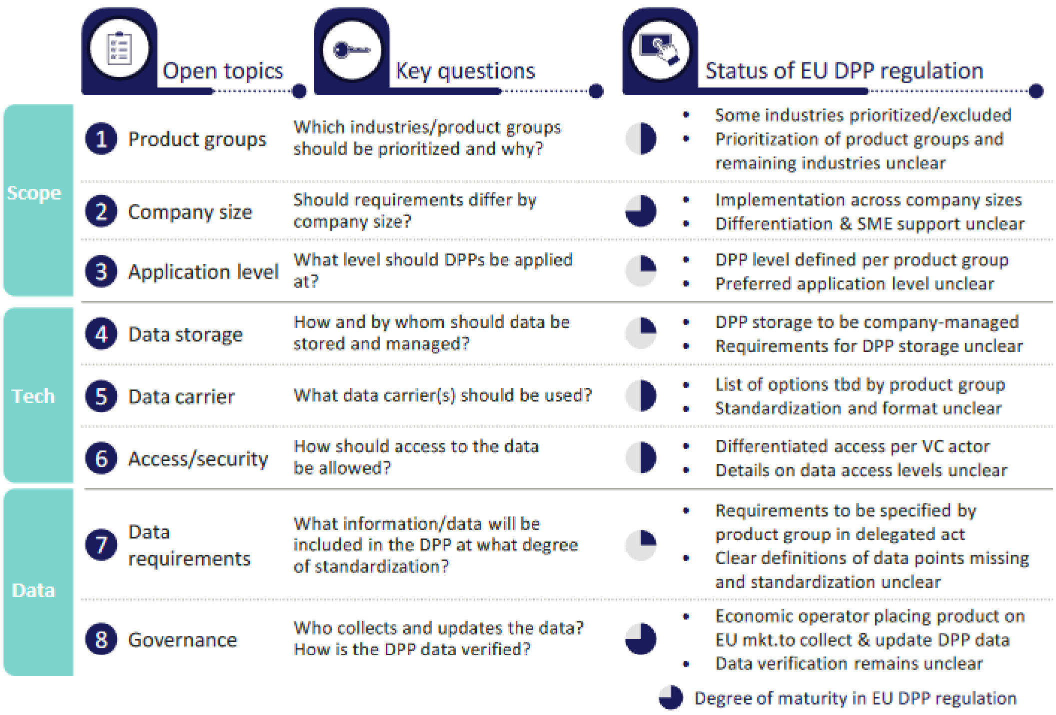

Figure 2.1: Overview of open topics in the DPP regulation
Source: [10, p. 11]

Application level: DPPs are suitable for implementation at different levels. Implementation can be either on the product level, batch, or item level. Implementing DPPs at the item level provides high precision and transparency by tracking each item's history of changes and repairs. On the other hand, DPPs can be implemented at a product model level, which causes a loss of transparency but makes it more simple and fast. Implementing DPPs at a batch level introduces a moderate level of complexity without significant environmental benefits, it limits product tracking to the earlier stages and only until the batch is disassembled.

Data storage: Optimizing data storage is advantageous as it decreases expenses and simplifies complexity. This objective can be attained through the EC offering explicit guidelines for a company-managed system based on a protocol for data sharing, or by utilizing an EU-managed platform, where the EC and companies have the flexibility to choose between centralized and decentralized storage approaches. Centralized storage, like cloud storage, is extensively adopted, straightforward to use, and cost-efficient. On the contrary, decentralized alternatives like DLT provide enhanced data security, transparency, and traceability, but with higher costs and lower prevalence.

Data carriers: Each product group will have a designated set of preferred data carriers. Regarding the Battery Regulation proposal, Quick Response (QR) codes are the favored data carriers due to their affordability, durability, and widespread usage. In general, various data carrier options exist, including technologies like digital watermark, Near Field Communication (NFC), and Bluetooth tags, as well as more established technologies such as barcodes and Radio Frequency Identification (RFID).

Data access: The EC aims to tailor data access based on stakeholder groups, granting each group access to the specific data they require. This approach aims to mitigate information overload and complexity. Alternatively, granting full access to all stakeholders raises concerns regarding data security and Intellectual Property (IP) protection. On the other hand, providing minimum access would compromise transparency and restrict the circularity potential of the DPP.

Data requirements: The proposal from the ECs suggests the adoption of comprehensive data categories encompassing aspects such as facile repair, service, upgrading, recycling, refurbishment, and specification of data points for each product group. While this approach would significantly benefit the environment, it would also introduce higher complexity and costs for companies. To assist companies in preparing for these data requirements, standardization of data could be implemented across industries. Alternatively, a hybrid approach involving both standardization and specific data point specifications could be considered.

Data governance: The EC proposes that the entity responsible for placing a product on the market should bear the legal obligation of collecting, providing, and maintaining the information within the DPP. To ensure improved data quality and establish trust, the inclusion of assurance could be explored. However, it is important to note that these approaches also introduce additional expenses for businesses.[10]

In general, a DPP can support the goals of a Circular Economy, which involves collecting information about a product from various stakeholders throughout its life cycle, such as manufacturers, retailers, consumers, and re-manufacturers, and creating a DPP for the product. This passport ensures easy traceability, returnability, and potential re-usability of the product. Furthermore, a DPP allows the monitoring of high-risk and high-value goods during transportation, storage, and use, thereby extending the product's lifespan. By doing so, DPP facilitates recycling, reuse of materials, proper disposal of harmful substances, and fosters research on improving material durability, reducing pollution, and increasing recyclability. [11]

The accompanying image in figure 2.2 illustrates how a Digital Product Passport can be introduced in a Circular Economy. It supports various key aspects, including sustainable recycling and manufacturing, by monitoring four crucial stages of a product: design, production, use, and recycling/reuse.

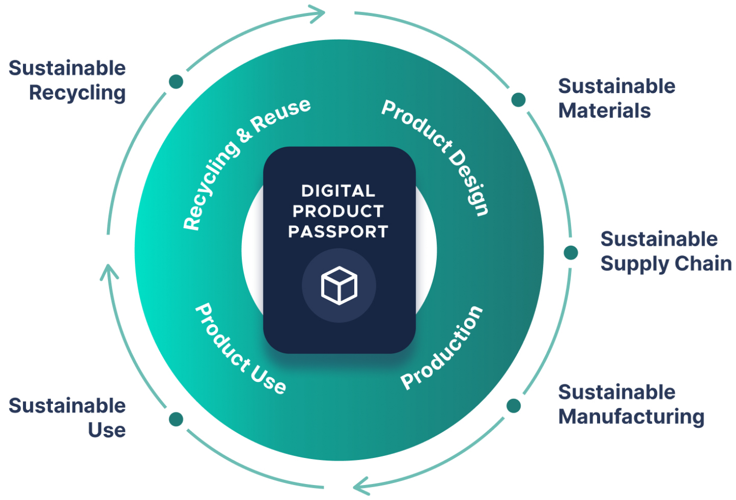

Figure 2.2: Digital Product Passport in the Circular Economy
Source: [11]

2.3 Blockchain

The blockchain is a shared digital ledger that stores data on multiple computers. The data is stored as records and transactions in a decentralized way and is therefore not controlled by only one or a few parties. The blockchain network consists of multiple nodes, frequently called peers, that maintain and validate the integrity of the ledger. The blockchain consists of blocks of data that are connected to each other and form a blockchain together. Besides the data, each block has a link to the preceding block. This connection of blocks results in the term blockchain.[12, p. 9] The reference to the previous block is a cryptographic hash that stands for the data within a block. This ensures that if someone would modify a block, the hash value would change and everyone on the network would recognize it as the hash value would differ from the hash that is saved in the next block. This makes the data of a blockchain immutable, and the user of a blockchain has proof of untampered data.[4, p. 133] Diverse consensus algorithms are utilized to establish consensus among participants regarding the state of the blockchain.

The implementation of the principles of a blockchain differ depending on the used blockchain, but at their core, they all follow the same principles, which are in conclusion:

- **Value Transfer**:
  The transactions recorded on a blockchain facilitate the direct transfer of monetary value between parties.
- **Data Storage**:
  Smart contracts and transactions can store information in blocks, which can be accessed and used depending on the application.
- **Smart Contracts**:
  Smart contracts, also called programmable contracts or chaincodes, allow the implementation of code to build decentralized and transaction-based applications. Further details on the topic of smart contracts will be explained in chapter 2.4.
- **Decentralization**:
  By ensuring that every participant in the network maintains a consistent copy of the blockchain, the need for a centralized entity to maintain the ledger containing all transactions is eliminated. This decentralized approach improves system robustness by reducing the impact of node failures and promotes network resilience and reliability.
- **Trust without Third Party**:
  On a blockchain, there is no need to rely and trust on a third party. The blockchain allows users to transfer values in a decentralized way.
- **Temporally Ordered**:
  Blocks on a blockchain are ordered, which means that the previous block always existed before the following block. Therefore, the information on the blockchain is ordered temporal and can be traced in time.
- **Immutable**:
  The transactions on a blockchain are immutable and cannot be changed. Therefore, the blockchain is an add-only data store that allows no modification of data including no updates and no deletes of transactions. This further implies that users can have assurance that the information stored on the blockchain remains unaltered.

- **Archival**:
  The complete transaction history on a blockchain is always visible. It is a data archive that allows tracking activities back to the very beginning of the ledger.[4, p. 146]

- **Transparent vs. Confidential**:
  Speaking of transparency and confidentiality, it becomes more complicated as these two goals stay in conflict. On a public and permissionless blockchain, there is high transparency as information about transactions can be read and verified by everyone on the network, which ensures trust in the information that is stored. Depending on the blockchain, there are also ways to hide information and only save the encrypted data to the blockchain. This enables saving sensitive data and still retains some transparency as the hashes are saved in the transactions. Nevertheless, full transparency gets reduced but increases privacy confidentiality in return.[13, p. 214] Especially in permissioned and private blockchains, confidentiality plays a much bigger role, particularly in scenarios involving sensitive data. While public blockchains prioritize transparency and pseudonymity, private and permissioned blockchains offer greater control over confidentiality by restricting access to trusted participants.[4, p. 146]

  In summary, when building a blockchain, the conflict can only be resolved by finding a balance between transparency and confidentiality that is compatible with the objectives of the solution. Generally, in public blockchains, the focus is on transparency and security, whereas in private blockchains for businesses, more emphasis is placed on confidentiality and speed.[13, p. 215]

The following chapters will further cover the topics of a blockchain that are important for this research in more depth.

2.3.1 Types of Blockchains

Blockchain technology encompasses various types of networks that differ in terms of accessibility, participation rights, and levels of decentralization. This chapter focuses on exploring four primary types of blockchains: public, private, permissioned, and permissionless blockchains. Each type offers distinct characteristics and is suitable for different use cases and environments, which is further illustrated in Table 2.1.

2.3.1.1 Public Blockchains

On public blockchains, all users, or nodes of the network have the right to create transactions and read from the blockchain.[13, p. 214] Public blockchains have no owner and therefore provide decentralization, as no party controls who can participate on the network.[14, p. 32]

2.3.1.2 Private Blockchains

Private blockchains limit the rights of reading access and creating new transactions to a closed group of users and nodes.[13, p. 214] With private blockchains there is no need to mine, the consensus works by just validating the transactions, which makes it much faster but less decentralized as the network is only accessible on a closed group of participants.[14, p. 566] Private blockchains only fit specific setups such as business environments where all participants are known. Especially with the need for privacy and confidentiality, private blockchains meet the security and privacy requirements businesses have.[14, p. 583]

2.3.1.3 Permissioned Blockchains

A permissioned blockchain, also called a permissioned ledger, is a blockchain where all the participants are known and trusted. This also means that only known participants can submit transactions. The parties, which can contribute to the consensus of the blockchain, are limited to a permissioned blockchain by restricting who can produce new blocks or participate as a miner.[15, p. 274] While participation on a permissioned blockchain is limited, it does not necessarily mean that it is a private blockchain. Instead, public blockchains can also be permissioned with regulated access control.[14, p. 33] Especially for business applications and operations between multiple organizations, permissioned blockchains are getting more and more prominent as they eliminate anonymity and only allow people that are known to submit transactions. On permissioned blockchains, it is not needed to run a proof of work algorithm that defends against the Sybil attack, which is an attack that works with fake identities, as all participants are known. Instead, the participants can run a deterministic distributed consensus algorithm. With this consensus algorithm, the participants only have to approve the last block that is added to the blockchain. This not only makes the consensus process much faster but also allows higher transaction volumes and delivers verifiable guarantees in terms of fault tolerance.[4, p. 147] The most prominent examples of permissioned blockchain systems are *Enterprise Ethereum*, *Hyperledger Fabric*, and *Corda*.

2.3.1.4 Permissionless Blockchains

On a permissionless blockchain, every user has writing access and access to verifying transactions and adding blocks.[13, p. 216] Such blockchains are completely decentralized and public and do not require approval for participating in the network. Examples of permissionless blockchains are *Bitcoin*, *Ethereum*, *Cardano*, *Avalanche*, and *Cosmos*.

	Public and Permissionless	**Public and Permissioned**	**Private and Permissionless**	**Private and Permissioned**
Transparency	Transparent for everyone.	Open but restricted.	Read transparent but restricted.	Restricted.
Rights	Write and read for everyone.	Write for everyone, read restricted.	Write is restricted, read for everyone.	Both, read and write are restricted.
Accessibility	Everyone can participate, transact, read, write, and verify.	Everyone can participate and transact. Read and verify only for permissioned users.	Everyone can participate but no transact, but everyone can read and verify.	Nobody can participate, transact, read or verify.
Validation	Any user can participate with validation transactions.	By meeting specified criteria, the user can participate with validation transactions.	Anyone within a closed network can participate with validation transactions.	Only a closed consortium of members can validate transactions.

Table 2.1: Types of Blockchains

2.4 Smart Contracts

The idea of smart contracts is relatively old and was first theorized in the late 1990s by Nick Szabo. Nowadays, with the innovation of *Bitcoin* and the growth of blockchain technology, the potential of smart contracts is highly valued now. A smart contract is a computer program, which embraces the agreement of different parties with the logic that is written in it. In a smart contract, the code gets triggered automatically when certain defined conditions are fulfilled.[14, p. 262]

Smart contracts are similar to written agreements, where the participating parties must negotiate on conditions until a mutual agreement is achieved. Smart contract code is executed by each node on the blockchain network in a distributed manner. Thereby, the blockchain does not require an additional trusted third-party middleman.[16, p. 74] The code of a smart contract is immutable, which means that it cannot change once deployed on the blockchain. This differs from traditional software. A completely new instance must be deployed if the smart contract must be modified. Furthermore, smart contracts are deterministic and therefore always have the identical outcome of the execution in the same context as the transaction that triggered its execution.[17, p. 128]

2.5 Hyperledger Fabric

Hyperledger Fabric, developed by IBM, serves as a fundamental platform for constructing modular systems with business cases. Its framework enables exchangeable components, like the membership and consensus services, while utilizing smart contracts, which are called chaincodes in *Hyperledger Fabric*, for defining conditions in code. The chaincodes encapsulate the application logic of the system.[18] This chapter aims to delve deeper into the design, architecture, components, and enterprise aspects of *Hyperledger Fabric*.

2.5.1 Ledger

The ledger is the database in a blockchain. A ledger is characterized by two rules: firstly, it is immutable and tamper-proof, and secondly, it is ordered by time. The database of the ledger is a binary file where the blocks are appended and replicated on each peer of the network.[19, p. 30] In *Hyperledger Fabric*, the ledger stores the value objects and the belonging transaction history. The immutable part of the ledger is that the state of the business objects may change, but the history of it is immutable and unchangeable. The ledger in *Hyperledger Fabric* is separated into two parts. One part is the world state database, and the other one is the blockchain itself, which will be described below.[20]

The world state database manages the present values of the ledger state and objects. It is separate from the ledger, which is used to record all performed transactions. Unlike the ledger, the world state database includes only the latest state of the transactions history and can change frequently, as the state can be created, updated, and deleted. Because of the small size of the world state database, *Hyperledger Fabric* allows efficient querying and analysis of assets. The implementation of a world state database is typically implemented with a key-value store, such as *LevelDB* or *CouchDB*.[18, p. 53]

The blockchain is the log of all the transactions that happened and resulted in changes in the world state. The transactions are gathered inside blocks and then get attached to the end of the blockchain. Every block has a header with the block's transaction hash, including the header of the prior block as a hash that connects them into a chain.[20]

2.5.2 Consensus Layer

The consensus layer is responsible for validating and ordering transactions, ensuring that the nodes on the blockchain have the same view of the status of the ledger to guarantee trust. In *Hyperledger Fabric* various types of consensus algorithms are possible to be implemented, in accordance with the demands of the network.[18, p. 54]

2.5.3 Ordering Service

For the ordering of transactions, *Hyperledger Fabric* provides a node called orderer or ordering node, which together with other orderer nodes forms the ordering service. Orderers regulate who has permission to participate in channels and who can write, read, or configure data on the channels. The ordering service is responsible for receiving transaction proposals from clients and ensuring valid and consistent transactions. Valid and consistent transactions get ordered and packaged into blocks and attached to the blockchain and updated on the connected peers. [19, p. 83] *Hyperledger Fabric* lets the developers decide which consensus algorithm and associated ordering service they want to utilize. The recommended implementation of *Hyperledger Fabric* is *Raft*, which is a Crash Fault Tolerant (CFT) ordering service. Crash fault tolerance means that when nodes get lost, the network remains intact. In *Raft*, there is a leader node that gets elected which then replicates its decision to all the followers, which is called *leader and follower model*.[21]

2.5.4 Peers

Peers are individual nodes that participate in the blockchain network and maintain a copy of one or multiple ledgers and chaincodes. They provide access to the blockchain and allow transactions to be submitted, validated, and committed to the ledger. *Hyperledger Fabric* has two types of peers. One type is the endorsing peer, which validates and signs transactions that exist on the blockchain. The validation and consistency of transactions are verified by the endorsing peer, which then adds its signatures to the transaction, endorsing the transaction and agreeing to add and update the transactions to the ledger. The other type is the committing peer that receives validated transactions from the ordering service and executes the addition to all the ledgers. Furthermore, committing peers maintain replications of the ledger and react to queries from other participating peers on the network. Users have to interact with their assigned peers to access the ledger, chaincode, and services provided by *Hyperledger Fabric*.[22]

2.5.5 Organizations

Organizations are groups of nodes that work together to maintain the blockchain network. An organization has a unique identity, defined by cryptographic keys, and is liable for handling its nodes. These cryptographic keys are used to sign and verify transactions and guarantee secure communication channels between nodes. The nodes of organizations act as peers, all with a replication of the blockchain ledger. Organizations can define policies for managing access to the nodes and resources, and can also define rules for the management of transactions within the network.[19, p. 74]

2.5.6 Identity and Membership Service Providers

To manage the access and the permissions over resources and information in a blockchain network, every actor has an identity in the form of an *X.509* digital certificate. Verified identities must be certified by a trusted authority, which in *Fabric* is the Membership Service Provider (MSP). [23] The MSPs are responsible for managing the identities of the participant in the blockchain network. [18, p. 666] MSPs define the rules that are used for creating, distributing, and verifying the certificates to the nodes and users. The participants of the network belong to one or more MSPs, where each MSP belongs to a parent MSP.[19, p. 76] As default, *Fabric* uses *X.509* certificates as MSP implementation, which works like a traditional Public Key Infrastructure (PKI). The certificates are distributed to the actors of the network by a Certificate Authority (CA). Fabric comes with its own CA called *Fabric CA*, which is capable of managing the digital identities of a *Fabric* network.[23]

2.5.7 Wallet

In blockchains, transactions only work with the usage of private and public keys, which are used for signing transactions and protecting the users' secrets. In this context, digital wallets allow users to securely store their keys, manage them and facilitate signing transactions.[19, p. 30]

2.5.8 Smart Contract/Chaincode

Smart contracts are code stored on the ledger. In *Hyperledger Fabric*, the smart contracts are also called chaincode. The code runs on transactions and modifies data of the world state when executed.[18, p. 53] Chaincode reflects the business logic of an application that is needed. The chaincode runs on the peers of a channel and can be executed by authorized members. With the definition of endorsement policies, the endorsers for transactions are specified, which also specifies the necessary peers that are needed for the trust assumption. The code can be written in different languages like *Go*, *Java*, *JavaScript*, or *Typescript*.[19, p. 80]

2.5.9 Private Data

Organizations within the network can keep data confidential between a selected set of organizations. Access to the private data can be facilitated, by saving it on databases of the organizations' authorized peers.[18, p. 54] By saving the hashed data on the ledger it is possible to conceal the actual data, but still make the transactions visible to all the participants.[18, p. 668] This only allows the organizations with the corresponding private data to recognize the sensitive data of the public transactions, by comparing the hashes of the public data with the hashes generated from the private data.

The owners of the private data can specify criteria that must be met before other organizations can access the data. For instance, policies for other organizations define access requirements for private data. If the requirements are fulfilled, the organizations can request admission to the private data. Subsequently, the data owner can grant access by updating the access control lists, which are defined by authorized organizations.

Especially for the related prototype of this thesis, private data is a very essential aspect, as the other participants in the life cycle of the Circular Economy still want to retain certain data confidential. *Hyperledger Fabric* organizations have the option to set up new channels that only allow access to this separated private data. Consequently, this comes with a lot of additional overhead and hides transactions from participants that have no access to these discrete channels. Therefore, another option called private data collection allows defining the collections for the data storage without opening an additional channel. The private data collections are defined in the definition of the chaincode where there is a reserved private data namespace.

Private data collections consist of two parts. The first part is the original data that is stored in a database located on the peers of the authorized organizations and sent peer-to-peer via a gossip protocol.
The second part is the hashed value of the original data that should be kept private. This part of the private data is registered to the ledgers on each peer and is visible to all participants to validate the transaction.[24]

It is possible to share private data collections between multiple organizations, and there can also be numerous collections within one channel. As there are also situations where there is the need of sharing the private data of one collection with other members or other collections, *Hyperledger Fabric* also enables the sharing of private data. Writing to the collections is also enabled for non-members if there are no restrictions against the policies. Furthermore, there is an Application Programming Interface (API) called *GetPrivateDataHash()* of the chaincode, which can be utilized to allow non-members access to the hash values of private keys.[24]

2.5.10 Endorsement Policy

Endorsement policies manage the set of signatures that are required for a transaction to be valid. The transaction can only be signed by the defined identities. An endorsement policy defines the members that are allowed to sign the transactions of a related smart contract.[18, p. 258]
Endorsement policies have a very straightforward and uncomplicated syntax:

$$EXPR(E[,E...])$$

An expression for the endorsement policy can either be an *AND*, *OR*, or *OutOf*. The E stands for a principal, which is a member of an assigned organization MSP, or another additional nested expression. [25]
Endorsement policies are something special in *Fabric* and differ from blockchains like *Bitcoin* and *Ethereum* with two benefits.
The first benefit of the *Fabric* blockchain technology is that organizations within a network can validate transactions on their own, unlike in public and permissionless networks, where the validation of transactions is done by external *mining* organizations. This approach provides more trust and finality to transactions, since all parties interested in the transaction are known to each other and can trust each other based on their identity. In contrast, *Bitcoin* and *Ethereum* rely solely on mathematical activity for transaction validation, which can result in recent transactions being reversed.
The second benefit of *Fabric* is that signature-based validation is very fast and

does not require a lot of computing power. In contrast, when using proof of work mechanisms like used in *Bitcoin* for example, the transaction validation process is very expensive and wastes a lot of energy due to unsuccessful computations of several miners. The validation of transactions in *Fabric* can be conducted cheaply and with low latency. This feature ensures that costs are shared with all the participants and no individual entity has to suffer from high transaction costs.[18, p. 260]

2.6 Blockchain in the Circular Economy

Blockchain and the Circular Economy have common aspects to bring out their full potential. Both concepts require a culture of collaboration, which feels very different for many companies, as they are used to keeping as much information as possible within the company. Furthermore, they consider regulations on their supply chain to have a negative impact on their business.

According to Phil Brown, Vice President of Business Development and Strategy at *Circularise*, a technology provider operating on the *Ethereum* blockchain, the effective utilization of blockchain in the Circular Economy requires the active involvement of an entire network of stakeholders. This involvement entails making fundamental changes to various aspects of their operations, which is not a straightforward task. Additionally, there is the concern that the dissemination of information could be exploited to drive down prices or question established practices.

However, the successful implementation of a Circular Economy, which requires a comprehensive shift in the entire system, can only occur when producers are financially motivated to design out waste from the outset.

With the integration of blockchain in the Circular Economy, new beneficial processes can be implemented. For example, scanning a specific material to assess its history, which triggers a preferred buyback option and shows which material supplier will repurchase the material at a predetermined value if the quality is maintained. Another feature is facilitating the recording of the location, quality, ownership, responsibility, and even payments for the transfer of materials through blockchain technology when integrated with a monetary transaction. Each phase of a product's life cycle can provide the necessary information for stakeholders from the blockchain to obtain the values they really need.

If blockchain can be further developed to enable such systems, it could empower businesses to genuinely take responsibility for the materials they select for their products. Their design choices would then more effectively close the loop in the supply chain for their operations and maximize the value streams within it. Blockchain could thus serve as the catalyst introducing the next phase of a Circular Economy.[26]

The use of blockchain technology holds significant promise for driving the shift to a more sustainable and Circular Economy. Blockchain's inherent characteristics of transparency, immutability, and decentralization offer a range of opportunities to transform various aspects of supply chains and consumer behavior. Subsequently, the key aspects and applications of blockchain in the Circular Economy are highlighted. Altogether, these blockchain-enabled solutions have the potential to change the manner in how we produce, consume, and manage resources, paving the way for a more sustainable and circular future.

- **Enhanced Transparency and Traceability**: Blockchain can provide a transparent and immutable ledger to record information about the origin, composition, and history of products and materials. This enables improved traceability throughout the supply chain, allowing stakeholders to verify claims and ensure adherence to sustainability and circularity standards.[4, p. 30]

- **Improved Supply Chain Management**: Blockchain-based platforms can facilitate an efficient and secured sharing of information among supply chain participants, enabling better coordination, collaboration, and visibility. This can streamline processes, reduce inefficiencies, and optimize resource utilization, contributing to a more circular and sustainable supply chain.[4, p. 30]

- **Trusted Data and Certification**: Blockchain can serve as a decentralized platform for verifying and certifying sustainability-related data, such as environmental impact assessments, certifications, and compliance records. This helps to establish trust and credibility among stakeholders, and to foster greater confidence in the circularity claims of products and materials.[4, p. 232]

- **Incentivizing Circular Practices**: Blockchain-enabled systems can introduce tokenized incentives and smart contracts that reward participants for adopting and promoting circular practices. For example, producers could be financially rewarded for designing products with recyclability and durability in mind, encouraging a shift towards a more circular business model.[19, p.40]

- **Collaborative Networks and Circular Ecosystems**: Blockchain can facilitate the creation of decentralized networks and ecosystems, bringing together various stakeholders involved in the Circular Economy. By enabling secure and transparent data sharing, blockchain fosters collaboration, innovation, and the development of new circular business models.[4, p. 260]

- **Circular Asset Tracking and Recovery**: Blockchain can help track and manage the life cycle of assets, enabling efficient recovery, refurbishment, and remanufacturing processes. By maintaining an auditable record of asset ownership, condition, and maintenance history, blockchain can optimize resource utilization and support the circular flow of materials.[4, p. 31]

- **Consumer Empowerment and Awareness**: Blockchain technology can empower consumers by providing them with access to verifiable information about the products they purchase. This enables consumers to make informed choices based on sustainability and circularity criteria, thereby driving demand for circular products and encouraging businesses to adopt circular practices.[13, p. 39]

3 Prototype Design

After understanding the core concepts of the Circular Economy together with the Digital Product Passport and DLT, including *Hyperledger Fabric*, the foundation to plan the design of a prototype is set. First, this chapter presents the design of the developed Circular Economy platform prototype, before discussing and explaining the most important design decisions made.

The prototype was designed with consideration of fulfilling the needs of an Digital Product Passport and providing the best possible transparency and traceability for materials of products within the Circular Economy. This chapter introduces the design of the prototype and the associated design decisions that had to be made to fulfill the requirements of a Circular Economy.

3.1 Design of the Digital Product Passport Platform

Before building the software solution that suits the use case, several factors that have an important impact in the given setting have to be examined and determined. The first factor of the platform is the Digital Product Passport itself and how it suits the set requirements. As shown in Figure 3.1, the Digital Product Passport is a record that exists for each individual product and hence includes the product name, a unique ID, and information about the manufacturer, value, and used materials. The information is represented in strings, for the *ID* it is simply the combination of a preferred identification style. The *name* is a simple string, and the manufacturer is the saved reference identification for the manufacturer on the network. For the identification of the owner, there is the *owner* field. For instance, this could be a simple consumer. The *appraised value* is a number that represents the price of the reselling value, and the *used materials* list is a list of strings that represent the hashes that are saved on the blockchain for the materials registered by a material producer. The whole record is saved on the blockchain where the information can either be visible to all the network participants or some of the records can be private, allowing access to the data values only to participants who are either the owner or have access. All other participants can still see cryptographic hashes of the data, ensuring transparency if some data changes during the product's lifetime. When it comes to the information about the product, the data is gathered from different sources that live on the blockchain or are saved and accessed from other databases. For instance, the resale value could be derived from a source with price indices for the specific product or materials. The data of manufacturing data comes from the product manufacturer itself and the materials from several producers together with other important information about the material that is important for reuse, recycling, or disposal. The data is transparent and visible on the permissioned blockchain. It only contains verified data, that is approved by participating organizations. For example, only material producers are allowed to register new materials. For other participants, changes will be visible and verifiable on the blockchain. Furthermore, not only the current values are visible, but also the history of past values of changed properties, increasing transparency even further.

Regarding the platform itself, one important factor is to understand the workflow of the most crucial scenarios in the application. These scenarios form the basic functionalities to be implemented with the problem solution.

Another crucial factor is the participation of different organizations in the business cases. The platform application should be constructed in a layout where all organizations can successfully contribute equally to the digital product passport platform.

Figure 3.2 on page 35 shows the most important organizations of the product passport platform together with their goals and responsibilities. The given scenario only shows one organization of each organization group to provide an easy overview. In a real-world application, multiple organizations of each group take part in a Circular Economy and build the whole ecosystem. The prototype aims to implement a solution that allows actors to carry out their tasks and responsibilities, as well as provide them with a solution that meets their interests via the prototype.

In the center of the illustration, there is the Product Passport Platform, which will be the application backend and database, including the blockchain. Most of the actors benefit from the product passport platform and have direct interactions with it. Only the consumer does not necessarily have to communicate via the platform as this would require a registration for each consumer, and in the given scenario the consumer does not have to interact with the platform. Still, in a real-world application, the consumer could also interact with the product

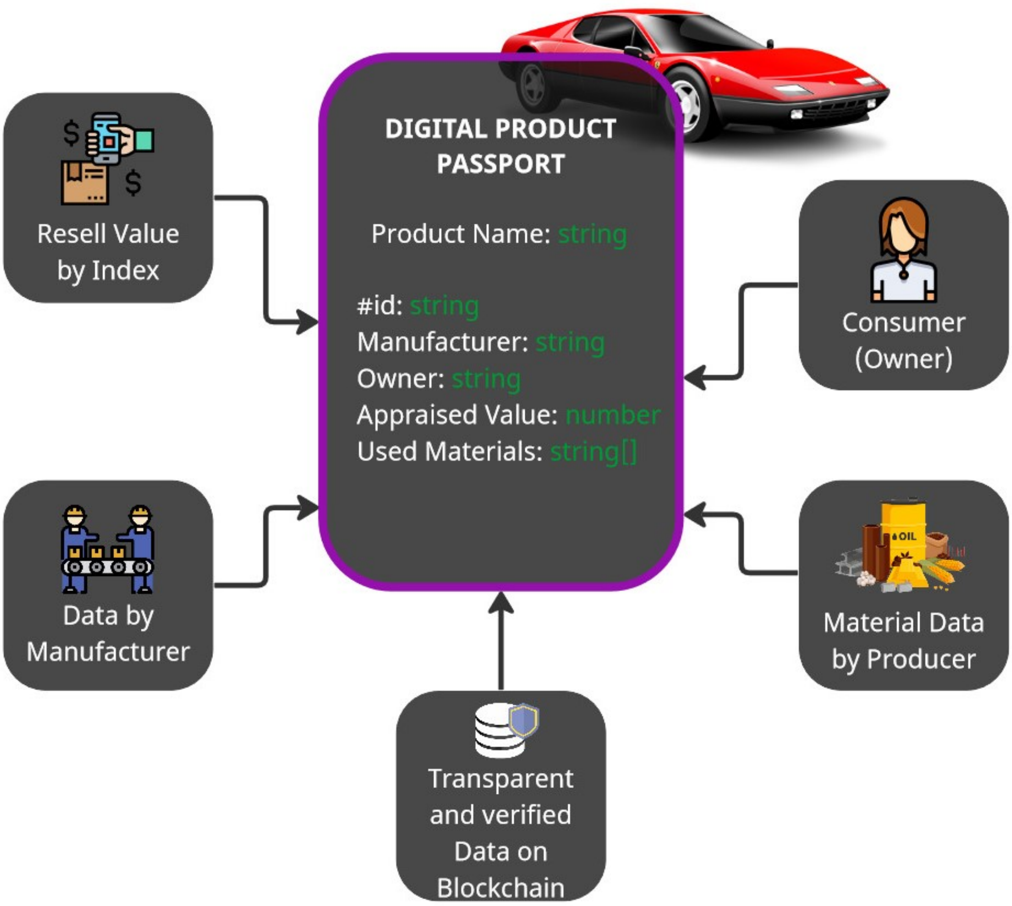

Figure 3.1: Digital Product Passport
Source: own figure

passport platform to request data about products and materials. The actors that directly interact with the platform are the material producer, the manufacturer, the recycler, and the regulation body, which could be a government for example. All these actors have to be specified in the blockchain application as organizations. Consequently, also the processes have to be represented and defined as chaincode. The implementation and definition will be described in the subsequent section of the design implementation and demonstration.

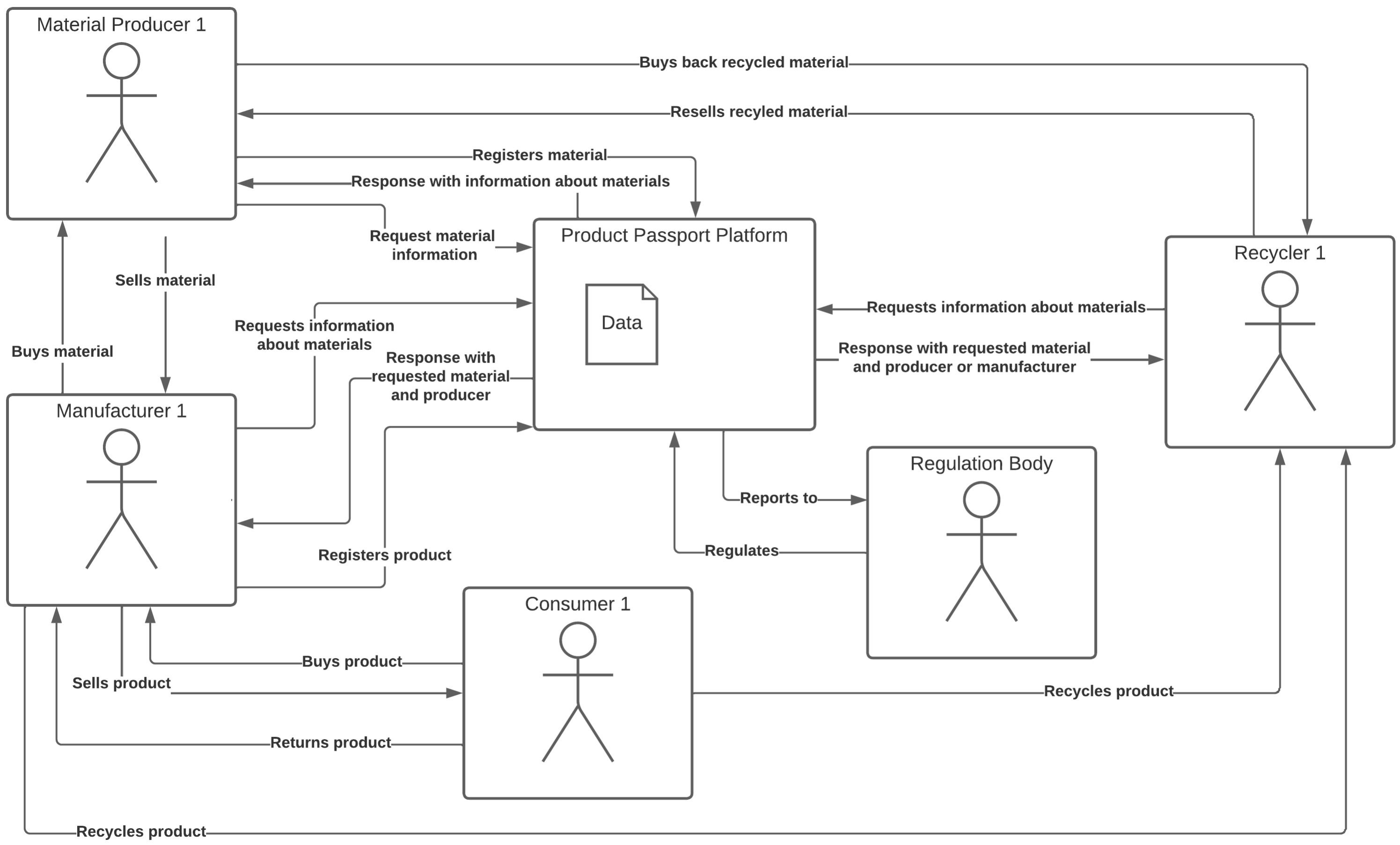

Figure 3.2: General Overview: Network interaction between Actors and Product Passport Platform.
Source: own figure

Within this ecosystem, all the processes that interact directly with the blockchain application and either write or read from it have to be transcribed as chaincode. To better understand how to write the code, the processes are split into separate use cases, which are also illustrated in Figure 3.2. The most important use cases are:

1. Registration of material by a material producer.
2. Registration of a product by a manufacturer.
3. Material producer sells material to a manufacturer that buys the material.
4. Recycler requests information about materials within a product and gets information.
5. Recycler resells the material to a material producer that buys back the material.
6. The manufacturer recycles a product.
7. Material producer or manufacturer requests information about a material and gets a response with the requested information.
8. The regulation body regulates how the data should look like.
9. Regulation body gets reports and monitors if everything complies with the law.

3.2 Design Decisions

3.2.1 Motivating Hyperledger Fabric

In the process of building a platform, various sorts of solutions can be considered to make products traceable and transparent. Table 3.1 shows a variety of frameworks in comparison. The comparison criteria include if the framework is decentralized and trust-free, how high the capacity of possible transactions is if it is permissioned, and how the consensus-building is implemented.

An Enterprise-Resource-Planning (ERP) solution is included in the comparison. ERP is a software solution that enables management for the entire organization due to its support in the automation of processes. As an ERP solution is not typically decentralized or trust-free, it does not possess those properties. However, it can have a high capacity, being designed to effectively manage a substantial influx of transactions and data. ERP solutions are typically permissioned, allowing authorized users within an organization to access and manage data. Consensus-building does not apply to ERP solutions, as they rely on predefined business rules and workflows rather than a consensus mechanism.

Bitcoin operates on a decentralized peer-to-peer network, distributing transactions and data across nodes. It establishes trust through consensus mechanisms and cryptographic techniques. *Bitcoin* has a low capacity, limited by its block size and block time. *Bitcoin* is a permissionless blockchain, allowing anyone to participate and transact on the network. Consensus in *Bitcoin* is achieved through the proof-of-work (PoW) algorithm.

Similarly, *Ethereum* operates on a decentralized network, distributing transactions and data across nodes. It achieves trust through consensus mechanisms and cryptographic protocols. *Ethereum* has moderate capacity, capable of handling a significant number of transactions. By default, *Ethereum* is permissionless, but permissioned implementations can be created. Consensus in *Ethereum* is currently achieved through a proof-of-stake (PoS) consensus mechanism called *Ethereum 2.0*.

Corda is a blockchain platform that operates on a decentralized network of nodes. It employs a decentralized architecture, distributing transaction processing and data storage across multiple nodes. *Corda* establishes trust within the network through cryptographic techniques and consensus mechanisms. It achieves high capacity, capable of handling a significant volume of transactions. *Corda* is designed as a permissioned blockchain, providing access control mecha-

Framework/ERP	Decentralized	Trust-free	Capacity	Permissioned	Consensus-building
ERP Solution	No	No	High	Yes	No Consensus building
Bitcoin	Yes	Yes	Low	No	Proof-of-Work
Ethereum	Yes	Yes	Moderate	Yes/No	Proof-of-Stake
Corda	Yes	Yes	High	Yes	Pluggable
Hyperledger Fabric	Yes	Yes	High	Yes	Pluggable

Table 3.1: Product Traceability and Transparency Solutions in Comparison

nisms and privacy features. Consensus in *Corda* is achieved through a pluggable consensus model, allowing participants to choose the consensus mechanism that aligns with their specific use case requirements. *Corda* focuses on facilitating secure and private transactions between known parties while preserving data confidentiality.

Hyperledger Fabric employs a decentralized architecture, with a network of peer nodes maintaining and validating the blockchain. It establishes trust through consensus mechanisms and cryptographic techniques. *Hyperledger Fabric* has high capacity, supporting large volumes of transactions and data. It is a permissioned blockchain framework, that provides access control and governance mechanisms. Consensus in *Hyperledger Fabric* is achieved through a pluggable consensus model, allowing participants to choose the consensus mechanism that suits their needs.

To guarantee transparent, traceable product data, a solution was sought that fulfilled all the criteria of decentralization, trustworthiness, high capacity, permissioned network, and consensus building. Decentralization ensures that no single entity has control over the data, promoting a distributed network where multiple participants can validate and contribute to the accuracy of product information. Being trust-free establishes a system where trust is not reliant on individual entities but rather on the consensus and integrity of the shared data. High capacity allows for handling a large volume of product data, accommodating the scalability requirements of comprehensive traceability. Permissioned access ensures that only authorized participants can contribute to and access the data, protecting against unauthorized modifications and maintaining data integrity. Consensus-building enables the collective agreement on the accuracy and validity of product data, establishing a trustworthy and transparent foundation for traceability efforts. Together, these criteria provide the necessary foundation for creating an implementation that fosters transparency, accountability, and traceability in product data, building equal trust among consumers and stakeholders. Only *Corda* and *Hyperledger Fabric* meet all these criteria and therefore are considered for the prototype implementation.

Hyperledger Fabric's higher degree of modularity and flexibility allows participants to tailor the network architecture and smart contracts to accommodate the specific requirements of Circular Economy processes. This customization capability enables the seamless integration of diverse systems and the implementation of complex business logic, making *Fabric* well-suited for the dynamic nature of Circular Economy applications.

While *Corda* has a strong focus on interoperability, *Hyperledger Fabric* also supports interoperability but offers more flexibility in terms of integrating with existing systems. The Circular Economy often involves collaboration between multiple organizations and the utilization of legacy infrastructure. *Fabric's* modular architecture enables easier integration with established enterprise environments, facilitating seamless data exchange and interoperability across different systems and stakeholders involved in Circular Economy initiatives.

The Circular Economy requires transparency, traceability, and efficient data sharing among participants to enable effective resource management and sustainable practices. *Hyperledger Fabric's* flexibility and scalability make it a suitable choice for implementing comprehensive Circular Economy solutions. *Fabric's* capabilities in handling large transaction volumes, supporting complex business processes, and accommodating diverse industry sectors make it well-suited for the various aspects of Circular Economy applications, including supply chain management, resource tracking, and product life cycle management.

While *Corda* excels in privacy and confidentiality, which can be important in certain use cases, the Circular Economy often requires a balance between privacy and transparency. *Fabric* provides privacy features through private collections, though it may not offer the same level of granularity as *Corda*. However, *Fabric's* strengths in modularity, customization, interoperability, and overall use case suitability make it a better choice for implementing an application focused on exchanging product and material data within the Circular Economy context.

3.3 Architecture and Components

3.3.1 Transaction Flow

Hyperledger Fabric has a modular design and uses a model *called endorse-order-validate*, which is designed for the distributed execution of code, and provides a reliable and scalable infrastructure for permissioned networks. The whole process can be observed in figure 3.3.

The first step is the endorsement of transactions. In *Fabric*, transactions are initiated by clients and proposed to the endorsing peers. These endorsing peers, which were discussed in 2.5.4 Peers in more detail, simulate the execution of the transaction and generate a proposal response, which includes the results of the simulation. The endorsement process ensures that the transaction is valid according to the chaincode logic and the endorsing peers' endorsement policies.

Once the transaction is endorsed, it needs to be ordered. In *Fabric*, endorsed transactions are bundled into blocks and the ordering service orders these blocks into a linear sequence called the ledger. The ordering service ensures consensus on the order of transactions among multiple ordering nodes. The order of transactions is important to maintain consistency across the network.

After the transactions are ordered, they are sent to the committing peers, which have already been discussed in 2.5.4 Peers, for validation and commitment. Committing peers perform the transactions again to guarantee that they are consistent with the present state of the ledger. This step is crucial for preventing malicious or faulty transactions from getting saved to the ledger. Committing peers apply the transactions to the state database and generate a validation result.[18, p. 59]

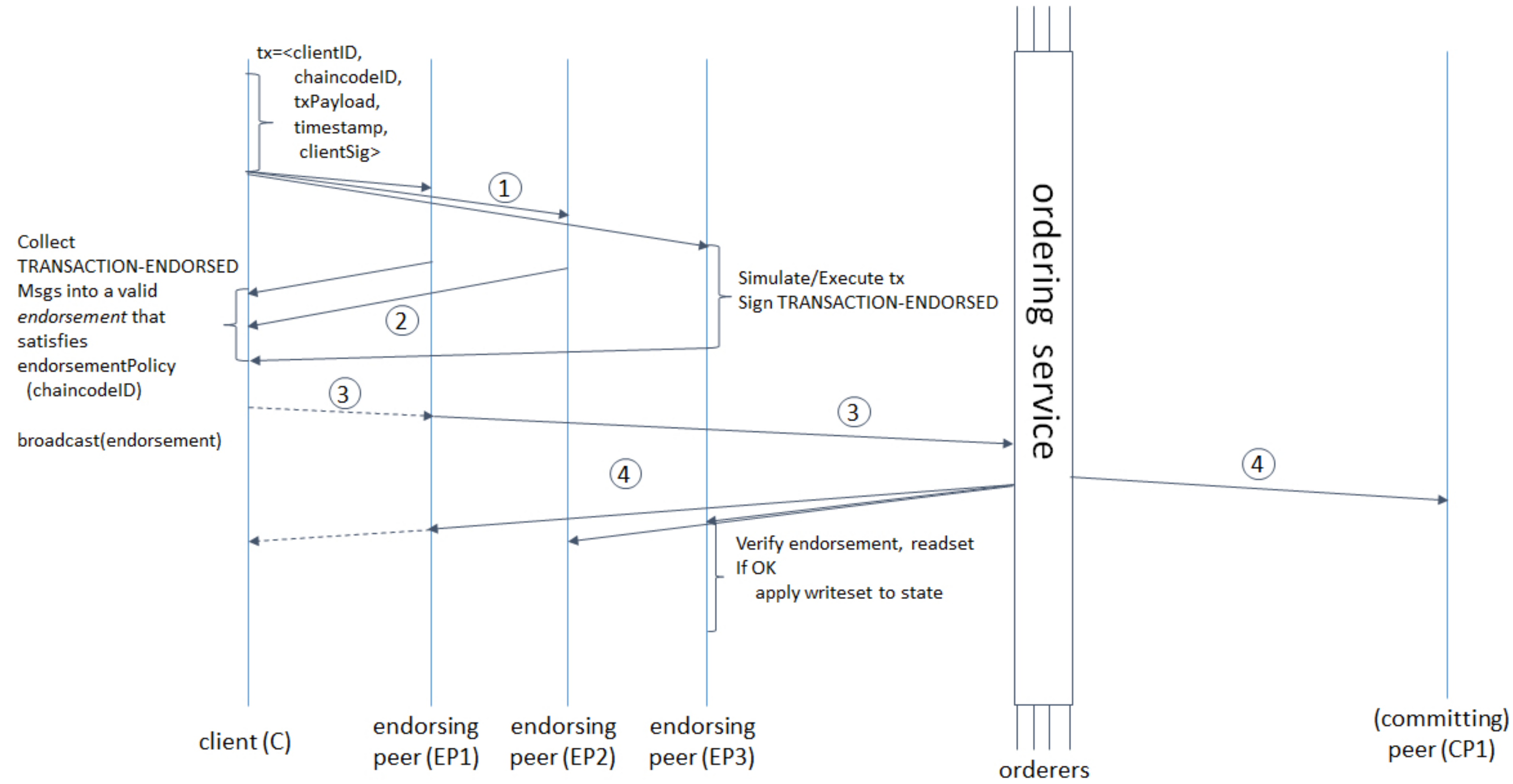

Figure 3.3: Transaction Flow of Hyperledger Fabric
Source: [27]

To make it more feasible, the following describes a scenario, where the transaction flow is described. The scenario involves a manufacturer that simply wants to register a product on the blockchain. The transaction flow would look like the following:

1. The registration process gets initiated by the manufacturer through the interaction with the blockchain, resulting in the generation of a transaction request. This request is then transmitted to the endorsing peers within the network.

2. The endorsing peers perform a simulation of the transaction by executing the chaincode logic, which includes validating the transaction against the predefined rules of the policies that set the rules for endorsement. Each endorsing peer endorses the transaction by applying the chaincode logic to the product registration data independently. The endorsing peers then return the endorsed transactions and the results to the client.

3. Once all the endorsed transactions have been collected from the endorsing peers, the manufacturer submits a proposal to the ordering service. The ordering service then arranges the transactions into blocks and facilitates a consensus mechanism to determine the sequence of the transactions.

4. The ordered blocks are then delivered to the committing peers that validate the blocks and write the transactions to their local ledger. When successfully written into the ledger, the committing peers send the acknowledgment back to the manufacturer. When the acknowledgment is received, the registration process is completed.

3.3.2 Hyperledger Fabric Infrastructure and Software Components

- **Hyperledger Fabric SDKs**:

  Hyperledger Fabric's Software Development Kits (SDKs) support different types of programming languages, such as *Node.js*, *Java*, and *Go*. These SDKs offer APIs and libraries that developers can use to interact with the Fabric network, submit transactions, query the ledger, and manage identities.

- **Hyperledger Fabric CLI**:

  The *Hyperledger Fabric* Commando Line Interface (CLI) provides a set of command-line tools that facilitate administrative tasks, such as creating and joining channels, installing and instantiating chaincode, managing identities, querying the state of the network, or testing transactions in a test-network environment.

- **Hyperledger Fabric CA**:

  The *Fabric* CA tool provides a secure way to manage identities, issue certificates, and handle the authentication and authorization of network participants. It is used for generating and managing the cryptographic material required for secure communication within the network.

- **CryptoGen**:

  In *Hyperledger Fabric*, *CryptoGen* can be used to generate cryptographic materials that are used for secure communications and authentication within the blockchain network. Such cryptographic materials are private keys as well as *X509 certificates.* An *X.509 certificate* is a digital certificate and standard for public key infrastructure (PKI) certificates. These certificates are important in guaranteeing identity and security in various forms of internet communication and computer networking.[28] The peers and users within the network are identified and authenticated using *X.509 certificates* that are distributed by a CA. With *CryptoGen* the private keys and *X.509* for these entities get generated.

4 Prototype Implementation and Demonstration

After explaining the design of the prototype, including the design decisions and architecture, the implementation and demonstration of the prototype can be discussed. This chapter describes how the prototype of the Product Passport Platform is implemented. In detail, an example of a complete product cycle in the Circular Economy as it could occur in reality is introduced to illustrate and explain the processes and implementation. Furthermore, the chapter involves the set-up of a test-network as well as the implementation and description of the chaincode, which is implemented for the described use case of the platform. The associated *Hyperledger Fabric* project can be found on the GitHub Repository: https://github.com/ffa6995/fabric-digital-product-passport. The documentation on the repository, as well as the code, can be consulted for a closer look at the implementation and functions mentioned in this thesis.

4.1 Introductory Example

In the Circular Economy, there is a variety of different actors that participate in the ecosystem. These actors could be producers, manufacturers, consumers, recyclers, or even regulatory bodies. The given scenario is about the different stages of a product that consists of multiple materials, which get recycled and reused as production resources for new products. The actors that participate in this process are the material producer, the manufacturer, the consumer, and the recycler. The material producer creates and provides the materials that are used to build different types of products. The manufacturer constructs products out of the materials he buys from material producers, which he then sells to end-consumers. Upon reaching the end of a product's life cycle, whether due to damage, simple use, or technical faults, the consumer gives the product to the recycler. The recycler breaks the product down again into different source materials, which he then sells back to the material producers. When breaking down the process of this scenario, there are a series of interconnected steps ensuring that the materials of a product are reused, recycled, and reintegrated into the production cycle:

1. **Material Production**: A material producer extracts and produces high-quality materials using sustainable practices. They prioritize renewable resources and employ environmentally friendly methods, minimizing waste and pollution.

2. **Material Procurement**: A manufacturer purchases the materials from the material producer to begin the manufacturing process. The manufacturer selects materials that are durable, recyclable, and align with their commitment to sustainability.

3. **Product Manufacturing**: The manufacturer designs and manufactures long-lasting, repairable, and upgradable products. The manufacturer prioritizes resource efficiency and minimizing waste generation during the production process. The products are designed to be easily disassembled, facilitating future recycling or repair.

4. **Product Distribution**: The finished products are distributed to consumers who appreciate the sustainable qualities of the products. Consumers use the products responsibly, extending their lifespan through proper maintenance and care.

5. **Product End-of-Life**: When the product reaches its end-of-life stage, consumers return it to the system instead of discarding it. They understand the importance of responsible disposal and recycling.

6. **Product Recycling**: A recycler collects returned products from consumers. They employ advanced recycling technologies to efficiently disassemble and sort the materials. The products are broken down into their constituent components, separating different materials for recycling.

7. **Material Reintegration**: The recycler transforms the recycled materials back into raw materials. These materials are then sold back to the material producer, completing the circular loop. The material producer can use these recycled materials to produce new products, reducing the need for virgin resource extraction.

By following this circular process, the product's materials are continually reused and recycled, reducing the reliance on virgin resources and minimizing waste generation. The materials flow in a closed loop, moving from the material producer to the manufacturer, then to the consumer, and finally to the recycler, before being reintegrated into the production cycle. This process helps to create a more environmentally friendly and efficient economy by reducing harm to the environment and making better use of resources.

4.2 Test-Network Setup

To properly implement a prototype, a test-network is needed to test and verify if the implemented chaincode and application logic works properly. The test-network is used to test the blockchain network together with the smart contracts and applications. Firstly, when setting up the test-network the peers with all the organizations, the ordering service, a channel, and all the associated certificates have to be generated. For testing, the *Fabric* network is deployed on *Docker* images on a local machine. For the setup, there is a script called *network.sh*, which can be found in the *test-network* folder. The script has different modes to start and set up the network together with its organizations, to stop the network, to create channels, and to deploy chaincode.

The first thing to do before starting a new test-network is to locate the destination folder and remove any container or artifact from previous runs with the down command. When starting the test-network all the peers together with the organizations and the ordering service are set up. Additionally, the channel for communications and transactions between the organizations is initialized. If the test-network is successfully deployed, there is one peer for each organization as well as an ordering service and the *Fabric* CLI on an allocated docker container up and running like shown in Figure 4.1. The test network only uses one single ordering service, while in a production network, there would be multiple ordering notes, that are operated by only one or multiple organizations. In the background, certificates, and keys for the organizations and orderer organization get created. This can either be done with the *Cryptogen* tool that was explained in 3.3.2 Hyperledger Fabric Infrastructure and Software Components or by a Certificate Authority.

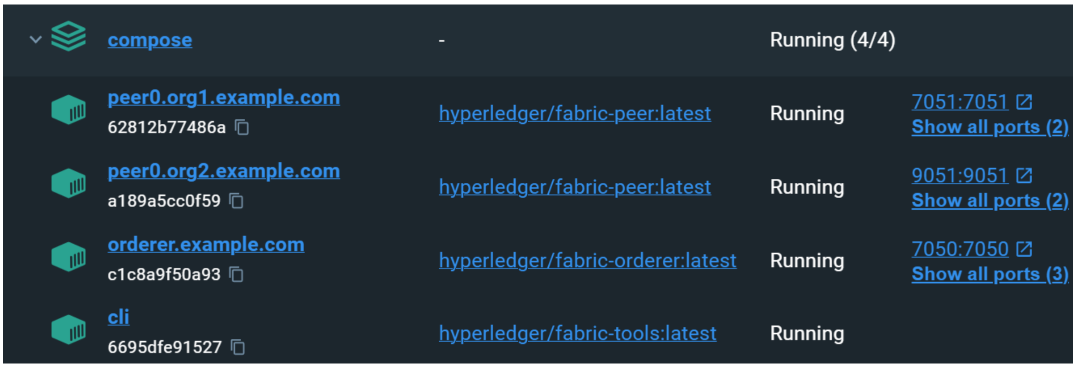

Figure 4.1: HyperLedger Fabric Network Setup on Docker Containers
Source: own figure

4.3 Chaincode Creation

As discussed in 2.5.8 Smart Contract/Chaincode, the chaincode is the code that implements the business logic and manages the world state of an object's life cycle. All of this runs for each peer on a separate *Docker* container, therefore all the peers must agree and approve the smart contract that is installed and deployed to the network. *Hyperledger Fabric* allows the developer to use their preferred programming language out of several supported languages like *Java*, *Go*, *JavaScript*, and *TypeScript*. The code of the following examples is written in *TypeScript*.

Chaincode in *Hyperledger Fabric* extends from the built-in chaincode class of the *fabric-contract-api* library. The *fabric-contract-api* gets installed as a dependency, which is defined in the *package.json* configuration in the chaincode project folder, which then can be added as import together with the needed classes to the chaincode.

For each business case that was defined in chapter 3.1 Design of the Digital Product Passport Platform there will be a function in the chaincode. The functions represent the business cases in code and enable the implementation of the transaction logic of the network.

The example of 4.1 Introductory Example is used as a demonstration of the implementation and to explain the functions and transactions that are called and executed by the associated organization. Furthermore, figure 4.2 shows all the participating organizations together with their processes and chaincode interactions. The interaction between the organizations that are carried out and executed as business processes are marked with the color blue. Likewise, the processes that happen within the organization are written in blue color. On the other hand, the red arrows show which chaincode functions are executed by which organization. Even more, they represent the necessary transactions for the implementation of the business processes to ultimately provide transparent and traceable data and thus also promote and support the Circular Economy.

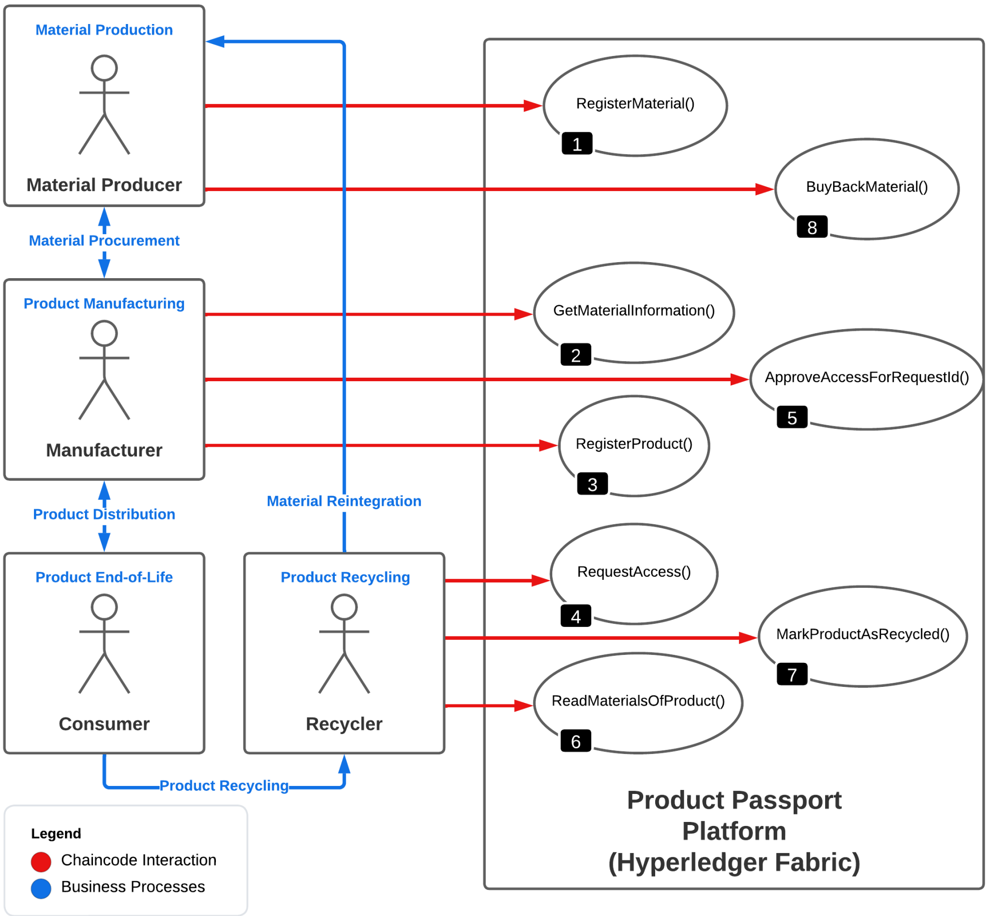

Figure 4.2: Business and Chaincode Interaction between Actors and Product Passport Platform
Source: own figure

4.3.1 Material Production

The process of the given circular product life cycle starts at the material producer. In the given scenario, the material producer is producing sustainable materials that are designed and intended to be reused as materials for new products at the end of a product life cycle. To guarantee the transparency of these materials, the material producer needs a way to register the material on the product passport platform, which is the *Hyperledger Fabric* blockchain. To register the material, the material producer uses the *RegisterMaterial* function, which is numbered [1] in figure 4.2. The function registers a new material by checking if it already exists, then creates a material object, and finally stores the object to the world state of the *Hyperledger Fabric* blockchain.

Listing 4.1 shows how this is implemented in the chaincode. The *@Transaction()* decorator in line one indicates that this function is a transaction function within the *Hyperledger Fabric* smart contract. Transaction functions are invoked by clients to perform specific operations on the ledger. The *RegisterMaterial* function takes several parameters:

- ctx (Context): The transaction context delivered by the runtime of *Hyperledger Fabric*.
- id (string): The identifier for the material being registered.
- materialName (string): The name definition of a material.
- producer (string): The producer of the material.
- appraisedValue (number): The appraised value of the material.

The function begins in line nine by checking if a material with the given ID already exists in the world state by calling the *MaterialExists* function. The *MaterialExists* function, which is shown from line 24 onwards, has the *@Transaction(false)* decorator indicating a read-only transaction function. Read-only transactions do not modify the ledger state, but only retrieve information from the world state. Inside this function, the *getState* function is called on the transaction's chaincode stub to retrieve the representation of the material of the given ID. With this, the logic of the function can then decide if the material already exists, depending on the existence of the material with the given ID. If the material exists, an error is thrown, indicating that the material cannot be registered again. This is implemented to reduce redundancy on the blockchain to save resources and remain data consistency and integrity. If the material does not exist, a new material object is created with all the provided details and then gets serialized into a string using the *stringify* function and recursively sorted by using the *sortKeysRecursive* function. This is done to ensure deterministic ordering of the properties for consistency. Finally, the serialized and sorted material object is stored in the world state using the *putState* function of the transaction's stub. The ID is used as the key, and the serialized material object is stored as a byte array after being converted using the *Buffer.from()* function.

```
@Transaction()
public async RegisterMaterial(
  ctx: Context,
  id: string,
  materialName: string,
  producer: string,
  appraisedValue: number
): Promise<void> {
  const exists = await this.MaterialExists(ctx, id);
  if (exists) {
    throw new Error(`The material ${id} already exists`);
  }

  const material: Material = {
    ...
  };

  await ctx.stub.putState(
    id,
    Buffer.from(stringify(sortKeysRecursive(material)))
  );
}

@Transaction(false)
 @Returns("boolean")
 public async MaterialExists(
   ctx: Context,
   id: string
   ): Promise<boolean> {
   const assetJSON = await ctx.stub.getState(id);
   return assetJSON && assetJSON.length > 0;
 }
```

Listing 4.1: Register Material Function

4.3.2 Material Procurement

The manufacturer designs and produces products for which he wants and needs to acquire materials to construct them. In this material procurement process, the manufacturer wants to get material information to check if the material from a specific producer meets the requirements and economic demands of the manufacturer. To do so, a function called *GetMaterialInformation*, numbered [2] in figure 4.2, is provided which takes a material identification and returns the material information about the given identification. This is also done by calling the *getState* function of the chaincode stub. If the function call returns a byte array, the material with the given identification exists and the function will return the material information as a *Material* object.

4.3.3 Product Manufacturing

When all the needed material is procured and the product is manufactured, the manufacturer needs a way to register the product to the product passport platform. For this, the *RegisterProduct* function, which is numbered [3] in figure 4.2 function, is implemented. The *RegisterProduct* function also accepts all the needed information like manufacturer, product name, and identification, but other than when registering a material it also accepts a list of materials that are already registered on the platform. Besides checking if the product already exists, all the submitted materials are checked on existence, as we only want products that consist of registered materials. If the checks pass, the materials get encrypted so that the composition of the materials is not publicly visible to all participants.

4.3.3.1 Implementation of Private Data

One very important requirement every participant wants is privacy. In particular, this includes the possibility to save data that is not accessible to everyone on the network but be unlocked for others if desired. Other participants still see changes to the data, as the hashed value of the data is stored on the blockchain for everyone to see within the network. Transparency for other participants is therefore not lost. With *Hyperledger Fabric*, all of this can be accomplished with private data collections that were already explained in the chapter 2.5.9 Private Data. In the given example of the product, there is a property called *Materials*, which should not be accessible to everyone. Only the product's manufacturer and approved entities are allowed to view the private data of the Material property.

When a product together with its materials gets registered on the network, the materials get hashed. The original material data gets saved in a private data collection, which is stored on authorized organization's peers. The ordering service has no permission to the private data. On the other hand, the hash of the data receives endorsement, and ordering, and is recorded in the ledgers of all peers within the channel. This hash serves as proof of the transaction and is utilized to validate the data state for auditing purposes.

To implement a private data collection, it is essential to develop a defined policy that outlines the participating organizations and specifies guidelines for handling private data. As some regulations stipulate that private data must be erasable, it is also possible to define the length of accessibility of private data on the blockchain. As shown in listing 4.2 the definition can be written as key-value-pairs in a simple JavaScript Object Notation (JSON) file.

```
[
  {
    "name": "privateMaterialsCollection",
    "policy": "OR('Org1MSP.member', 'Org2MSP.member')",
    "requiredPeerCount": 1,
    "maxPeerCount": 1,
    "blockToLive": 1000000,
    "memberOnlyRead": false,
    "memberOnlyWrite": false,
    "endorsementPolicy": {
      "signaturePolicy": "OR('Org1MSP.member')"
    }
  }
]
```

Listing 4.2: Private Data Collection Definition

The *name* property is used as the name of the collection and simultaneously serves as an access variable to the collection. Here, the name is the *privateMaterialsCollection*.

With the *policy* property, the policy for the private collection is defined. Setting the policy to *OR('Org1MSP.member', 'Org2MSP.member')* means that only members from either *Org1MSP* or *Org2MSP* are allowed to access this collection.

The *requiredPeerCount* property defines the minimum number of peers that must endorse transactions related to this private collection. Here, it is set to 1, meaning that at least one peer must endorse a transaction involving this collection for it to be considered valid.

The maximum number of peers that can endorse transactions related to the private collection is defined with the *maxPeerCount* property. In this case, it is also set to 1, indicating that a maximum of one peer can endorse transactions involving this collection.

To define how many blocks the data in this private collection should be kept alive, the *blockToLive* property can be set. Here, the set value is 1,000,000 blocks, so the data remains on the network for a very long duration.

To set whether only members who are part of the collection's policy can read the data, the *memberOnlyRead* property can be set to either true or false. Here it is set to false, so more granular access control can be implemented in the chaincode. This is helpful because access control and ownership of the product the private collection belongs to could be changed.

The *memberOnlyWrite* is also a boolean value indicating whether only members who are part of the collection's policy can write or modify the data. Here, it is set to false, implying that members not belonging to *Org1MSP* or *Org2MSP* can also write to this collection. Again, the permissions could change if ownership of the product is changed. Therefore, the access for this is also defined in the chaincode.

The endorsement policy for the private collection is defined with the *endorsementPolicy* property. It specifies the criteria for endorsing a transaction involving this collection. In this example, the endorsement policy is defined as follows: *signaturePolicy*: *OR('Org1MSP.member')*, which means that any transaction involving this collection must be endorsed by at least one member from *Org1MSP*. This allows overwriting chaincode-specific policies. Even if the chaincode policy is set to require endorsement by Org1 or Org2, we can set that only Org1 is allowed to invoke chaincode that writes data to the private collection.

In the *RegisterProduct* function, each material gets hashed with the *generateMaterialKey* function and then put into the collection holding the private data. This is done by using the *putPrivateData* function of the chaincode stub.

The function accepts the private data collection, the hashed material value, as well as the original material value as arguments. With this combination of data, the owner as well as accepted entities can access the private data collection with the material hash and retrieve the original data from it. To hash the material objects, the *SHA-256* hashing algorithm is used. First, the material objects get serialized into a string, which is then passed to the *createHash("sha256")* function. With the *digest("hex")* method, the hash value then is computed and returned as a hexadecimal string, which results in the value that is saved for the representation of the original material data.

4.3.4 Product Distribution

When the product is sold to an end consumer, the process of product distribution starts. In the example, the consumer is not registered to the product passport platform and therefore the manufacturer takes all necessary steps for transferring a product. The manufacturer invokes the *TransferProduct* function with the *productId* and the new owner. The identification of the owner could be anything suitable for identification so that every organization would be able to identify this owner by it. For example, in the European Union, this could be a passport number or digital identity number. By invoking the *TransferProduct* function, number [4] in figure 4.2, the existence of the product is checked, and if the product exists the owner gets overwritten and the updated product object is put in the new state.

4.3.5 Product Recycling and Material Reintegration

Like mentioned before, in the given scenario consumers have no direct interactions with the product passport platform and therefore the product end-of-life process has no direct influence on the platform. When the product is recycled by the consumer, the process of product recycling begins, whereby the recycler decomposes the product back into various original materials. To do this, the recycler needs information on the materials, which is not visible to anyone other than the producer and approved organizations. Hence, it is necessary to establish a mechanism through which the recycler can request access to the required information via the Product Passport Platform. This is made possible with the *RequestAccess* method, which is numbered [5] in figure 4.2. The transaction takes the product identification and first checks if the product exists and if the caller does not already have access to the data. If there is already permission, an error is thrown and the transaction is interrupted. If the caller does not have access, the caller identification is pushed into the *ApprovalRequests* array of the requested product object, and then the product object gets updated to the world state. After the request of the recycler, the manufacturer can either accept or decline the request by calling the *approveAccessForRequestId* function, which is number [6] in figure 4.2. The parameters for this function are again the involved product identification, the identification of the requesting participant, which is the recycler, and if the manufacturer wants to approve. Foremost, the usual checks are conducted to check if the product exists and if the caller is the manufacturer, as only the manufacturer is allowed to approve access. When the manufacturer has passed a *true* value for the *approved* parameter, the requested identification gets pushed to the *ApprovedEntities* array of the product. Immediately after, either if approved, or declined, the requested identity gets removed from the *ApprovalRequests* array and after that, the product is set to the new state.

With approved access, the recycler now can call the *ReadMaterialsOfProduct* function, which is number [7] in figure 4.2, and retrieve the material information that is needed for the recycling process. In the function, the product's existence and if the caller is the manufacturer or any approved entity of the product is checked. Upon successful authorization and access to the private data collection, the material hashes stored within the product object are utilized to retrieve the corresponding private data from the collection. Subsequently, this data is provided to the recycler. Right after, with the *RecycleAndOffer* function, which is number [8] in figure 4.2, the recycler can mark the product as recycled and offer the materials for sale again. This function simply updates the product's *Recycled* property, which is a boolean, to *true* and then puts the updated product object to the new world state. Furthermore, it registers the recycled materials with a new seller identification, as well as a material identification consisting of the original identification and the addition *RECYCLED* to the product platform. That way, the producers can see that a specific recycler offers the materials for sale. The producer can simply use the *GetMaterialInformation* function, number [2] in figure 4.2, with the identification of the searched material together with the *RECYCLED* addition and then gets material information with the seller. With this information, the material producer can buy back the material and reprocess them, completing a circuit of the product cycle and thus supporting the goals of the Circular Economy.

5 Results and Analysis

After presenting the design of the prototype based on the literature review and explaining and demonstrating the implementation, this chapter summarizes and analyzes the results. This chapter reviews the established requirements of the Circular Economy and the Digital Product Passport and verifies whether and how these have been solved by the implementation of the prototype. Furthermore, the outcomes of the prototype design and implementation are evaluated and analyzed whether the goals of chapter 1.2 Objectives have been achieved.

5.1 Challenges of the Circular Economy

In Chapter 2.1.1 Circular Economy Principles, Models, and Challenges, the principles that the Circular Economy is based on were introduced. Particularly, the principles with the context for transparency and traceability of products and materials were explained in detail. The principles are *design out waste*, *build resilience through diversity*, *think in systems*, and *waste is food*. This chapter revisits these principles and explains how the implementation of the prototype has incorporated them.

One main principle is the *design out waste* principle. This principle states that waste is the result of bad design decisions. The solution of the prototype was designed with the end-of-life of products and materials in mind. With the product passport platform, a solution is provided that allows participants of the Circular Economy to easily access the data that is required to disassemble, reuse, or repair products and materials and therefore also reduce waste.

Build resilience through diversity is another principle of the Circular Economy that recognizes that incorporating diverse elements in systems enables greater adaptability to changes and enhances overall resilience by providing alternative options, redundancy, and innovative capacities. The platform allows various resources, suppliers, and markets on and ensures transparency over the whole circular process. With this approach, over-reliance on a single supplier is avoided and an open, fair, and transparent market is promoted.

In addition to the implementation, the principle of *think in systems* is applied. This principle uses a system thinking approach that considers the interconnections of the whole system with all its components. The product passport platform allows collaboration and coordination among various stakeholders, including businesses, regulation bodies, and consumers. It provides a transparent solution to understand the interconnections as well as to identify opportunities to optimize resource use, reduce waste, and create positive feedback loops.

With the principle of *waste is food* in a Circular Economy, the waste of one process should become the resource for another process. The resulting solution of this thesis allows identifying from where and which producer or manufacturer a material, a product, or even parts of that product come from. This allows reselling of materials or products that would be thrown away as waste back to the producers and manufacturers, where they can again use them as feedstock for production.

5.2 Challenges of Sustainable Resource Management

Sustainable Resource Management is another approach that was explained in chapter 2.1.2 Sustainable Resource Management and introduced principles that benefit the Circular Economy as well as create new economic opportunities and innovations. These principles were also considered during the implementation of the solution.

The principle of *resource efficiency* is like the *design out waste* and *waste is food* principle of the Circular Economy, as it also emphasizes promoting sustainable production and consumption by tracking materials of products for easy reuse. Furthermore, the Circular Economy principle of SRM is similar to these principles, as it also emphasizes using the waste from one system and using it as a resource of another system. The product passport platform makes it possible to examine which materials a product is made of and which manufacturer it comes from. This eases reuse as the needed data is accessible to resell the material back to the producers, and also for the producer or manufacturer to repurchase materials that are needed for production.

Life cycle thinking is another principle that emphasizes the comprehensive evaluation of a product's entire life cycle, spanning from production to disposal. This approach enables the identification of areas where resource efficiency can be enhanced, and garbage reduction can be achieved. With the traceability of the products and materials and the transparency the product passport platform provides, the whole product life cycle is open accessible, and visible to network participants. In turn, this offers participants opportunities to find life cycle improvements within the Circular Economy to work more efficiently and with less waste.

By using the collaborative platform of the prototype solution, the principle of *sustainable procurement* is applied as sustainable production and consumption is promoted. Recycled materials can be bought back by the original or other manufacturers, which simplifies the procurement process and even makes it cheaper.

Another principle is *stakeholder engagement.* It emphasizes involving as many stakeholders as possible in the decision-making process, thereby increasing transparency and accountability of sustainability. With the transparency of occurring transactions on the blockchain, the product life cycle is traceable and participants can see where problems occur that negatively impact the reusability of materials and products. Furthermore, the stakeholders can decide if the materials correspond to their needs and requirements, as the data is transparent and changes to the products or materials are openly visible. Even if the data is private, stakeholders still can see on the changed value of the hashes, that are saved on the blockchain, that something changed.

5.3 Challenges of the Digital Product Passport

The Digital Product Passport by the European Commission, which was introduced in the chapter 2.2 Digital Product Passport, defined some open questions that still have to be answered and served as a guide for working on the common goals of the European Commission's Digital Product Passport and the goals of the Circular Economy. This chapter serves to answer the open questions based on the developed prototype and to make recommendations.

Since this research has a technical context, especially the technical questions, and questions that deal with data management are interesting to be answered. These are also the questions that are mostly undefined by the European Commission yet.

Tech:

- **Data storage**: "How and by whom should data be stored?"
- **Data carrier**: "What data carrier(s) should be used?"
- **Access/security**: "How should access to the data be allowed?"

Data:

- **Data requirements**: "What information/data will be included in the DPP at what degree of standardization?"
- **Governance**: "Who collects and updates the data? How is the DPP data verified?"

The first technical question concerns data storage. In the prototype solution, the most important data that should be transparent and accessible by every participant is stored decentralized on the blockchain. This ensures the required transparency for a working Circular Economy ecosystem, and together with private data collections still ensures that sensitive data can be hidden from other participants on the network. Other detailed product data like documents and images should be stored on an off-chain database, which is relational, non-relational, or distributed. This ensures that the blockchain network is not overloaded with a too high volume of data, as it would slow down the network.

For the data carriers, which connect the physical product with the data, there are multiple options, and depending on the product group there could be more suitable data carriers than for others. In general QR codes are easily applicable, affordable, and widely used, but there are also data carriers, like NFC or RFID that could be used. Providing an exact answer to this question is outside the scope of this thesis and is highly dependent on government regulations.

Access to the data is granted by registering the organization to the blockchain network. The scope of access should depend on the stakeholder group, and they should only gain access to the data they need or are allowed to see. Limited access to data also damages transparency. With the blockchain, this issue is solved by providing hashed transaction information that is accessible to everyone on the network. When the data is needed by a participant and access is granted, the hidden data can be revealed.

Data requirements will also depend on standardized data requirements, which probably will be depended on the industry of the product. The product passport of the prototype uses simple data objects, which can be converted to simple JSON, or string data, to be as comprehensible as possible and applicable to the prototype.

As also suggested by the EC, the implementation of the prototype requires that the data, of those who have produced a product or material, are registered, collected, and made available to the network. However, the updating of the data is done automatically through the transactions of the network participants and only needs to be verified and confirmed by the producers and manufacturers or by a regulatory body.

5.4 Review of the Research Questions

This chapter showcases the outcomes and analysis derived from the conducted research, aiming to address the two research questions outlined in chapter 1.1 Research Questions. The chapter starts with a summary of the solutions developed to tackle the research questions, followed by an examination of the constraints and limitations encountered. Finally, recommendations for future improvements and implementations are provided.

The primary questions for the research of this master's thesis are:

1. **How can traceability and transparency of materials used in products in the Circular Economy be enabled with the integration of a Distributed Ledger Technology solution?**
2. **How might a prototype with the integration of smart contracts and Distributed Ledger Technology look like?**

To enable traceability and transparency of materials used in products within the Circular Economy, a blockchain solution is implemented using *Hyperledger Fabric*. The solution aims to provide a secure and transparent tracking mechanism for materials and products throughout the supply chain, while maintaining privacy through private data collections. The developed solution leverages the immutability and decentralized nature of DLT to record and track the movement of products together with their materials from their origin back to the recycling process and reuse for new products. Each product has a unique identifier, and its relevant information, such as manufacturer, and materials, and recorded on the DLT. This allows stakeholders to access a tamper-proof and transparent history of each product together with its materials, ensuring traceability and accountability.

5.5 Limitations

In this section, the limitations of the provided prototype are discussed. Despite the successful implementation of the DLT solution, several limitations were identified during the research. These include:

- **Scalability**: The scalability of the DLT solution needs to be addressed, particularly when dealing with large-scale Circular Economy networks involving numerous stakeholders and transactions. To include end consumers in blockchain interaction, they must all register on the blockchain with unique IDs. This would multiply the number of transactions and network load by a large factor. Further research is required to explore solutions that can handle increased transaction volumes without compromising performance.

- **Data Input Reliability**: The accuracy and reliability of data input into the DLT system heavily depend on the data sources and the trustworthiness of the involved parties. Ensuring data integrity and preventing malicious actors from entering false information require additional measures, such as data verification mechanisms and trusted data sources. Several regulatory bodies can potentially be crucial in validating the accuracy of the entered data.

- **Interoperability**: Integrating the DLT solution with the existing data management systems of the companies and Circular Economy participants may pose challenges due to differing data formats, protocols, and governance structures. Future efforts should focus on developing standardized interfaces and protocols that promote seamless interoperability across various platforms and systems.

5.6 Recommendations

This chapter presents recommendations for researchers and practitioners who are interested in developing similar solutions to enable traceability and transparency of materials used in products within the Circular Economy through the integration of a DLT solution. Based on the findings and analysis of this research, the following recommendations are provided:

1. **Considering the Contextual Requirements**: When developing a solution for traceability and transparency in the Circular Economy, it is crucial to consider the specific context and requirements of the industry or sector in focus. Understanding the unique challenges, stakeholders, and regulatory frameworks is key when designing a tailored solution that addresses the specific needs and constraints.

2. **Choosing the Right Distributed Ledger Technology**: Evaluating and selecting the most appropriate DLT platform for the solution is very important. *Hyperledger Fabric*, utilized in this research, is a permissioned blockchain framework suitable for enterprise use. However, depending on specific requirements, other DLT platforms such as *Ethereum*, or *Corda* may be more suitable. Factors like scalability, privacy, consensus mechanisms, and interoperability should be considered in the decision-making process.

3. **Designing a Robust Data Model**: Developing a comprehensive data model that captures the necessary information about materials, products, and their life cycle stages is recommended. Considerations about incorporating unique identifiers for each product and associated materials to facilitate efficient tracking and traceability should be made. Data integrity, security, and interoperability should be assured by following established standards and protocols. Depending on the upcoming regulations of various countries and the European Union, there will be standardization that companies will have to follow to organize their data accordingly.

4. **Collaborating with Industry Stakeholders**: Engaging with key stakeholders in the Circular Economy, including manufacturers, suppliers, distributors, and recycling facilities is recommended. Collaborative efforts are crucial to ensure the adoption and success of the traceability solution. Seeking input and involvement throughout the development process to gain valuable insights and address practical challenges effectively can be beneficial. Especially, when building a collaborative platform, it is crucial to meet all the needs of the participants and provide a solution that is compatible with the interfaces of the participants.

5. **Addressing Privacy and Security Concerns**: The importance of privacy and security should be recognized when implementing a DLT-based solution. Mechanisms to protect sensitive information should be developed. This could be proprietary formulations, or trade secrets, while still maintaining transparency and traceability for the materials used in products. Employing encryption techniques, access controls, and identity management protocols to safeguard data integrity and prevent unauthorized access is also very helpful.

6. **Promoting Standardization and Interoperability**: Another recommendation is to support the adoption of standardized data formats, protocols, and interfaces within the Circular Economy ecosystem. It is recommended to encourage collaboration among different organizations and industries to establish common frameworks that facilitate seamless data exchange and interoperability between various DLT platforms and existing systems.

By following these recommendations, researchers, and practitioners can contribute to the advancement of traceability and transparency in the Circular Economy, fostering sustainability, accountability, and responsible resource management.

6 Conclusion and Future Work

In this master thesis, the research questions regarding the enablement of traceability and transparency of materials used in products within the Circular Economy through the implementation of a DLT solution have been addressed. Through the implementation of a blockchain solution using *Hyperledger Fabric*, a secure and transparent tracking mechanism for materials and products throughout the supply chain has been developed. The solution leverages the immutability and decentralized nature of DLT to record and track the movement of products, along with their associated materials, from their origin to the recycling process and reuse for new products. By implementing a DPP and assigning each product a unique identifier and recording relevant information on the DLT, stakeholders can access a tamper-proof and transparent history, ensuring traceability and accountability. The findings of this research demonstrate that the integration of a DLT solution can contribute significantly to enhancing traceability and transparency in the Circular Economy. It enables stakeholders to make informed choices, promotes responsible resource management, and supports the transition to circular and sustainable production and consumption. While this thesis has given a valuable understanding of the integration of DLT for traceability and transparency in the Circular Economy, several areas warrant further exploration. Future work in this field can focus on the following aspects:

- **Scalability and Performance Optimization**: As the volume of transactions and data increases within the Circular Economy, it is important to address scalability and performance challenges. Further research can explore techniques and optimizations to enhance the scalability of the DLT solution, enabling it to handle a larger number of transactions and accommodate a growing network of stakeholders.

- **Interoperability and Integration**: To achieve widespread adoption and maximize the benefits of traceability solutions, interoperability with existing systems and integration with other emerging technologies should be considered. Future work can focus on establishing interoperability frameworks and exploring the integration of DLT with Internet of Things (IoT) devices, artificial intelligence, or data analytics to enhance data collection, validation, and analysis capabilities.

- **Privacy-Preserving Mechanisms**: While transparency is crucial for traceability, the protection of sensitive information and privacy rights should also be considered. Future research can investigate privacy-preserving mechanisms, such as zero-knowledge proofs or secure multi-party computation, to ensure the confidentiality of proprietary information while still enabling transparent tracking and traceability.

- **Adoption and Governance Models**: Understanding the factors that influence the adoption and governance of DLT-based traceability solutions is vital. Future work can focus on studying the barriers and enablers of adoption, evaluating different governance models, and identifying strategies to create incentives for stakeholders to participate in the traceability ecosystem.

- **Social and Economic Implications**: Exploring the broader social and economic implications of implementing traceability and transparency solutions in the Circular Economy is an important area for future research. This includes analyzing the impact on consumer behavior, market dynamics, and policy-making processes to assess the overall effectiveness and sustainability of such solutions.

- **User Experience and Interface Design**: Enhancing the user experience and interface design of traceability systems can further drive their adoption and usability. Future work can focus on developing intuitive user interfaces, conducting usability studies, and integrating user feedback to optimize the usability and accessibility of the solution for various stakeholders. An easily accessible, as well as understandable, interface for the use of DLT would contribute significantly to loosening the barriers to its use.

By addressing these areas of future work, researchers, and practitioners can continue to advance the field of traceability and transparency in the Circular Economy, contributing to a more sustainable and accountable global supply chain.

In conclusion, the integration of a DLT solution for traceability and transparency in the Circular Economy holds great promise. This research has demonstrated the potential for DLT to enable secure and transparent tracking mechanisms, fostering responsible resource management and supporting the transition to a more circular and sustainable future.

Bibliography

[1] United Nations. "THE 17 GOALS | sustainable development." (2023), [Online]. Available: https://sdgs.un.org/goals (visited on 06/01/2023).

[2] Ellen MacArthur Foundation, "Towards the circular economy: Economic and business rationale for an accelerated transition," 2013. [Online]. Available: https://emf.thirdlight.com/file/24/xTyQj3oxiYNMO1xTFs9xT5LF3C/Towards%20the%20circular%20economy%20Vol%201%3A%20an%20economic%20and%20business%20rationale%20for%20an%20accelerated%20transition.pdf (visited on 04/04/2023).

[3] P. Lacy, J. Long, and W. Spindler, *The Circular Economy Handbook: Realizing the Circular Advantage*. London: Palgrave Macmillan UK, 2020, ISBN: 978-1-349-95967-9 978-1-349-95968-6. DOI: 10.1057/978-1-349-95968-6. [Online]. Available: http://link.springer.com/10.1057/978-1-349-95968-6 (visited on 06/27/2023).

[4] N. Vyas, *Blockchain and the Supply Chain: Concepts, Strategies and Practical Applications*. 2022, ISBN: 978-1-398-60523-7.

[5] M. Frąckiewicz. "The benefits of DLT for traceability and transparency in supply chains," TS2 SPACE. (Apr. 19, 2023), [Online]. Available: https://ts2.space/en/the-benefits-of-dlt-for-traceability-and-transparency-in-supply-chains/ (visited on 06/27/2023).

[6] European Commission. "Circular economy action plan." (Mar. 2020), [Online]. Available: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en (visited on 04/04/2023).

[7] Tandem. "What is the circular economy?" (May 22, 2020), [Online]. Available: https://tandemcircular.com/what-is-the-circular-economy/ (visited on 06/27/2023).

[8] United Nations Economic Commission for Europe, *United Nations Resource Management System: An Overview of Concepts, Objectives and Requirements* (ECE Energy Series). United Nations, Jun. 11, 2021, ISBN: 978-92-1-005309-9. DOI: 10.18356/9789210053099. [Online]. Available: https://www.un-ilibrary.org/content/books/9789210053099 (visited on 04/13/2023).

[9] World Business Council for Sustainable Development, "The EU digital product passport shapes the future of value chains: What it is and how to prepare now," Dec. 2022. [Online]. Available: `https://www.wbcsd.org/contentwbc/download/15584/226479/1` (visited on 04/13/2023).

[10] World Business Council for Sustainable Development, "Enabling circularity through transparency: Introducing the EU digital product passport," Jan. 2023. [Online]. Available: `https://www.wbcsd.org/contentwbc/download/15585/226483/1` (visited on 04/13/2023).

[11] IOTA Foundation. "Digital product passport," IOTA Foundation Blog. (Jun. 23, 2022), [Online]. Available: `http://blog.iota.org/digital-product-passport/` (visited on 06/15/2023).

[12] E. Elrom, *The Blockchain Developer: A Practical Guide for Designing, Implementing, Publishing, Testing, and Securing Distributed Blockchain-based Projects*, 1st ed. Apress, Jul. 24, 2019, 532 pp., ISBN: 978-1-4842-4846-1.

[13] D. Drescher, *Blockchain Basics: A Non-Technical Introduction in 25 Steps*. 2017, ISBN: 978-1-4842-2603-2.

[14] I. Bashir, *Mastering Blockchain: Distributed ledger technology, decentralization, and smart contracts explained, 2nd Edition*, 2nd ed. Packt Publishing, 2018, 658 pp., ISBN: 978-1-78883-904-4.

[15] V. Dhillon, D. Metcalf, and M. Hooper, *Blockchain Enabled Applications: Understand the Blockchain Ecosystem and How to Make it Work for You*, 1st ed. edition. New York, NY: Apress, Nov. 30, 2017, 240 pp., ISBN: 978-1-4842-3080-0.

[16] P. De Filippi and A. Writh, *Blockchain and the Law: The Rule of Code*. Harvard University Press, Apr. 9, 2018, 292 pp., ISBN: 978-0-674-97642-9.

[17] A. M. Antonopoulos and G. Dr. Wood, *Mastering Ethereum: Building Smart Contracts and Dapps*. 2019, ISBN: 978-1-4919-7194-9.

[18] N. Gaur, A. O'Dowd, P. Novotny, L. Desrosiers, V. Ramakrishna, and S. A. Baset, *Blockchain with Hyperledger Fabric: Build decentralized applications using Hyperledger Fabric 2, 2nd Edition*, 2nd ed. edition. Packt Publishing, Nov. 27, 2020, 756 pp., ISBN: 978-1-83921-875-0.

[19] M. Zand, B. Wu, and M. A. Morris, *Hands-On Smart Contract Development With Hyperledger Fabric V2: Building Enterprise Blockchain Applications*. O'Reilly Media, Sep. 28, 2021, ISBN: 978-1-4920-8612-3.

[20] Hyperledger. “Ledger — hyperledger-fabricdocs main documentation.” (2023), [Online]. Available: https://hyperledger-fabric.readthedocs.io/en/release-2.5/ledger/ledger.html (visited on 05/09/2023).

[21] Hyperledger. “The ordering service — hyperledger-fabricdocs main documentation.” (2023), [Online]. Available: https://hyperledger-fabric.readthedocs.io/en/release-2.5/orderer/ordering_service.html (visited on 05/09/2023).

[22] Hyperledger. “Peers — hyperledger-fabricdocs main documentation.” (2023), [Online]. Available: https://hyperledger-fabric.readthedocs.io/en/release-2.5/peers/peers.html (visited on 05/09/2023).

[23] Hyperledger. “Identity — hyperledger-fabricdocs main documentation.” (2023), [Online]. Available: https://hyperledger-fabric.readthedocs.io/en/release-2.5/identity/identity.html (visited on 05/11/2023).

[24] Hyperledger. “Private data — hyperledger-fabricdocs main documentation.” (2023), [Online]. Available: https://hyperledger-fabric.readthedocs.io/en/release-2.5/private-data/private-data.html (visited on 05/09/2023).

[25] Hyperledger. “Endorsement policies — hyperledger-fabricdocs main documentation.” (2023), [Online]. Available: https://hyperledger-fabric.readthedocs.io/en/release-2.5/endorsement-policies.html (visited on 05/11/2023).

[26] C. Murphy. “How blockchain can facilitate the transition to a circular economy.” (2023), [Online]. Available: https://ellenmacarthurfoundation.org/tech-enablers-series/part-2 (visited on 06/09/2023).

[27] Hyperledger. “Transaction flow — hyperledger-fabricdocs main documentation.” (2023), [Online]. Available: https://hyperledger-fabric.readthedocs.io/en/release-2.5/txflow.html (visited on 06/22/2023).

[28] Sectigo. “What an x.509 certificate is & how it works,” Sectigo® Official. (Jan. 7, 2021), [Online]. Available: https://www.sectigo.com/resource-library/what-is-x509-certificate (visited on 06/28/2023).

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