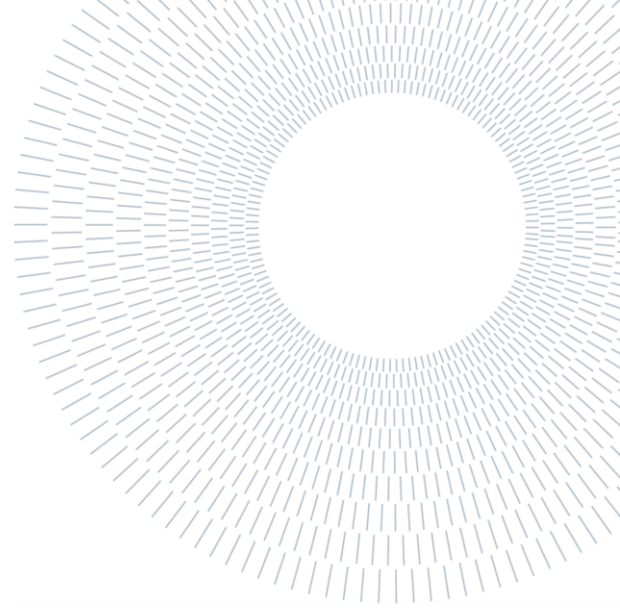




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EXECUTIVE SUMMARY OF THE THESIS

# The Role of the Digital Product Passport in Unlocking Second-Life Opportunities for Batteries

TESI MAGISTRALE IN MANAGEMENT ENGINEERING – INGEGNERIA GESTIONALE

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## 1. Introduction

In recent years, the strategic role of batteries has increased significantly, especially in the transportation sector, in response to European goals of achieving climate neutrality. The rapid growth in demand has led to an acceleration in production, which, considering environmental, geopolitical, and sociotechnical challenges, is no longer sustainable. Introducing Circular Economy (CE) strategies and ensuring second-life options for End-of-Life (EOL) products is the solution recognised by the European Union. In fact, the EU established a regulatory framework for CE, which includes the Ecodesign for Sustainable Product Regulation (ESPR) and the EU Battery Regulation. To guarantee transparency, traceability, and standardisation for a variety of product types, including batteries, the Digital Product Passport (DPP) is a crucial tool in this regard. The implementation of the DPP, which is anticipated to become mandatory by 2027, has the potential to introduce new ideas and approaches for the circular economy of batteries.

This thesis focuses on the European context and aims to understand how European regulations, especially the DPP, can unlock second-life opportunities for EOL batteries.

## 2. Theoretical background

The research is based on the principles of the circular economy, which aims to move beyond the linear “take-make-dispose” model by keeping products and materials in use for as long as possible. In the electric vehicle battery sector, the circular economy is crucial for reducing dependence on critical raw materials, enhancing end-of-life management, and achieving European climate targets.

In this scenario, the EU regulatory framework – from the Green Deal to the Circular Economy Action Plan and the Ecodesign Regulation for Sustainable Products (ESPR) – introduces tools such as the Digital Product Passport, made mandatory by the Battery Regulation (EU 2023/1542) from 2027 for the main categories of accumulators. The DPP, integrated into the principles of extended producer responsibility (EPR), enables transparency and traceability

throughout the value chain, serving as the starting point for DSS that can reduce uncertainty and facilitate new opportunities for second-life use.

### 3. Thesis Objective

The thesis objective of unlocking second-life opportunities through the exploitation of the DPP and establishing a unified framework for identifying second-life applications through secure data exchange has been pursued over three main sub-objectives:

1. Mapping the closed-loop battery value chain to overcome the existing fragmentation in understanding battery flows, stakeholders and circular strategies across the lifecycle. The aim is to provide a comprehensive, qualitative picture that combines industrial practices and regulations.
2. Designing a Decision Support System (DSS) to build upon the qualitative insights generated through the value chain mapping, to establish a structured framework that can guide second-life decision-making.
3. Demonstrating practical application through use cases to demonstrate the applicability and usefulness of the DSS, integrated with the DPP, in real scenarios. Additionally, a concrete application of selected use cases to the company Envirobat España wants to enhance how the developed tools can support increasing safety, effectiveness, and compliance at critical points in an industrial value chain.

### 4. Methodology

The study is structured in the following way. It begins with an analysis of the battery industry and regulatory landscape to connect market practices with the Battery Passport framework. From this, a detailed value chain mapping was developed, focusing on business, material, and information flows, especially DPP data attributes. Building on this foundation, a Decision Support System was created to guide second-life decisions, and several use cases were formalised to illustrate its practical application.

The following tools and approaches were utilised to pursue the three sub-objectives:

1. Value chain mapping and analysis: The value chain was developed following the guidelines and directions of MacCarthy et al. [1]. Indeed, after a definition of the boundaries, a graphical representation was proposed, including economic entities (nodes) and the connections between them (links) and the flows that characterise them. The mapping was conducted using a qualitative approach, drawing on multiple data sources and integrated with the regulatory framework.
2. Design of a Decision Support System – IDEF0: The construction of the DSS was made possible thanks to the qualitative insights generated in the value chain mapping. In particular, the identification of stakeholders, their interactions, and the corresponding R-strategies provided the foundation for defining the decision functions and the relationships between different stages of the battery life cycle. The DSS has been designed using the IDEF0 methodology, which provides a function modelling method where each function is enriched with data and objects that interrelate those functions, including inputs, outputs, controls, and mechanisms. The functions represent actions that are, in this specific case, aligned with the post-use value chain actions. [2]  
The proposed IDEF0 diagram maps information flow and decision logic across functions, making interactions straightforward to understand.
3. Development of Use cases – UML: The use cases are selected considering relevant phases of the value chain mapping and DSS structure. They have been modelled utilising the UML (Unified Modelling Language) methodology that allows for the representation of the system's functionalities from the perspective of the involved actors. Diagrams show the necessary information flows, the system functionalities involved, and the actions taken by the actors. [3]  
In addition, CIRPASS's procedures and the Battery Pass's framework for use case development were used as support to thoroughly define the use case's

applicability along the value chain, including scenarios with and without the DPP, required and optional data, and the benefits (economic, environmental, and social). [4]

Finally, the use cases contributed to an iterative amelioration of the DSS by testing its assumptions.

## 5. Results

The findings from this thesis are examined in this section.

### 5.1. Value Chain

The creation of a thorough representation of the battery value chain, including its commercial, informational, and physical aspects, was the main research outcome. This is shown in Figure 5.1. The mapping identified the numerous actors involved and highlighted the system's complexity. For each actor, both material and informational inputs and outputs were analysed, including mandatory and voluntary data requirements set out in the digital product passport. This approach enabled the identification of critical points in the chain, including the traceability of critical materials, determining the health status of batteries, and risk management during collection and dismantling. In addition, the value chain developed provides a solid methodological basis for quantifying the functions and benefits of DPP integration, offering a structured view of value creation opportunities from a circular economy perspective.

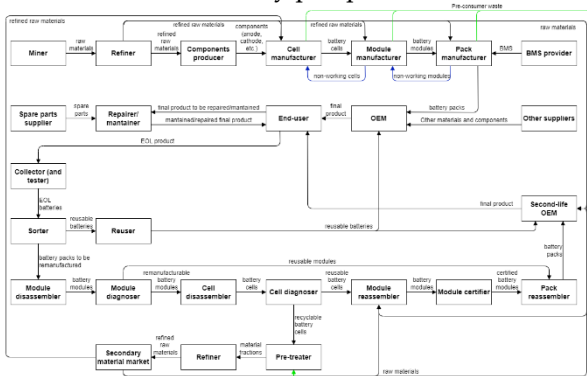


Figure 5.1: Battery Value Chain

Additionally, a DPP-centric value chain was constructed to connect the actors involved to the phases of the DPP. Particularly, the actors

interacting with it are linked to the stages of the DPP lifecycle.

### 5.2. Decision Support System

The research led to the development of a decision support system (Figure 5.2) designed to automate and enhance decision-making processes related to EOL EV battery management. The system utilises data from the product's digital passport. It integrates information from the Battery Management System (BMS) and external sources, including market prices and technical requirements for various applications, which are stored in an external database. Through IDEF0 modelling, it has been possible to translate the complexity of the decision-making process into a clear structure that can link inputs, outputs, controls, and resources. In this sense, the DSS becomes a tool for comparing different scenarios and choosing the best option among recycling, remanufacturing, and reuse, as well as for particular applications, rather than just providing a technical or financial outcome. The system's ability to guarantee traceability and consistency across the value chain, directly connecting decisions to the different actors involved, is what distinguishes it as innovative. A vital operational tool for lowering risks, minimising uncertainty, and converting legal requirements into workable business procedures is the DSS.

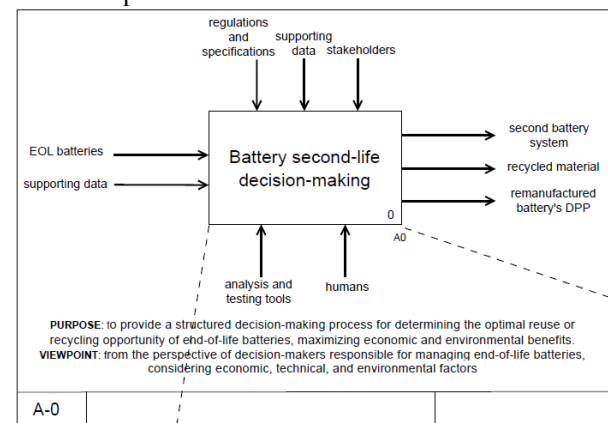


Figure 5.2: Decision Support System

### 5.3. Use cases

Several use cases were developed to concretely demonstrate how DPP data and the integration with the DSS can be utilised to support decision-making along the battery value chain.

The following use cases have been developed, covering diverse phases in both the pre-use and post-use stages, with a particular focus on remanufacturing.

1. Eased repair to extend the battery life
2. Technical evaluation to define the most suitable second-life application
3. Simplified residual value determination
4. Comprehensive battery risk assessment
5. EV battery reuse in Energy Storage Systems
6. Data aggregation from multiple DPPs
7. Circularity impact computation
8. Traceability across multiple lives
9. Anomaly detection
10. Disassembly facilitation
11. Eased custom compliance

Each case highlights the economic, environmental and social benefits of access to standardised data, such as reduced testing costs, greater opportunities for safe reuse, increased transparency for buyers and optimised material recovery. These scenarios not only demonstrate the practical relevance of the DPP but also provide strategic guidance to supply chain actors on how to maximise circularity and safety in second-life operations.

To determine how they can support an industrial process centred on battery recycling and remanufacturing, a few selected use cases are further examined and mapped along Envirobat's line.

## 6. Discussion

By mapping material and information flows and elucidating the institutional, supply chain, and firm-level challenges that businesses encounter, the battery value chain offers a comprehensive overview of all stakeholders. The absence of a secure, standardised, and transparent way to exchange data is one of the most critical gaps in the literature that the Digital Product Passport addresses. The DPP facilitates compliance with regulatory targets on recycled content while lowering uncertainty in design, sourcing, and end-of-life management by enabling traceability. The Decision Support System builds on this foundation by converting the available data into organised decision-making procedures. It not only lessens internal barriers, such as short-term financial

reasoning, but also guides the decision between recycling and second-life pathways in line with both economic and environmental goals. These tools work together to lower costs, improve interoperability, strengthen supply chain resilience, and extend product lifetimes. By doing this, they tackle the systemic problems of the circular economy as well as the challenges of the EV battery market. Along the way to a universal standard for second-life applications, they also promote regulatory alignment, improve operational efficiency, and open up new markets, making the battery supply chain more competitive and sustainable. Ultimately, the thesis develops a system that supports stakeholders in transitioning to a circular economy, helping them reduce costs—particularly in activities related to second-life—while meeting environmental goals, with the overarching aim of unlocking second-life opportunities for end-of-life batteries.

## 7. Conclusion

In conclusion, this thesis aims to unlock and ease second-life opportunities through the development of tools that support second-life decision-making for batteries.

The results highlight the potential of DPP not only as a regulatory requirement, but also as a strategic lever to enable new second-life opportunities, strengthen supply chain resilience and align industrial, social and environmental objectives. In this way, the thesis helps bridge the gap between regulatory ambitions and industrial practices by proposing a replicable framework that can support the transition to a competitive and sustainable model for the entire battery sector.

### 7.1 Limitations and Future Development

To improve the DSS by incorporating algorithms for calculating performance and residual value, and testing them on actual cases, future research should validate the suggested value chain information flow with stakeholders. To supplement existing qualitative insights, quantitative modelling of costs, environmental, and social impacts is required. Contractual relationships between post-use actors should be examined, the model should be extended beyond the EU, and the analysis of safety risks along the

value chain should be improved. Finally, specific research is needed on understudied topics, such as data granularity, DPP stakeholder roles, second-life opportunities, and the deactivation scenario, to ensure effective and timely DPP implementation.

## References

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## 8. Acknowledgements

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