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

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Abstract

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 strategies and ensuring second-life options for end-of-life products is the solution recognised by the European Union. The regulatory framework established over the past two years encompasses requirements and regulations related to batteries and waste batteries, including the introduction of the Digital Product Passport (DPP) for batteries.

The DPP aims to enhance information sharing, data availability, traceability, and transparency throughout the battery value chain, storing all data attributes regarding the battery and its environment.

This study leverages the definition of DPP requirements for batteries to unlock second-life opportunities by combining regulatory analysis with a decision-making framework. The research analysis included an in-depth preliminary investigation of the relevant regulatory framework and available second-life opportunities, based on the battery's State-of-Health. The ultimate goal was pursued through the development of a comprehensive closed-loop battery value chain and a Decision Support System (DSS) that uses the DPP and supplementary data sources to identify the optimal second-life application for a specific battery. Finally, several use cases were developed along the value chain to assess the impact of integrating the DPP and the DSS in the pursuit of a circular economy. Selected use cases were applied to the industrial case of Envirobat España to demonstrate the practical applicability of the comprehensive systems.

Key-words: Circular Economy, Digital Product Passport, Battery second-life, Decision Support System, Use case, Electric Vehicles, Remanufacturing

Abstract in italiano

Negli ultimi anni, il ruolo strategico delle batterie è aumentato in modo significativo, soprattutto nel settore dei trasporti, in risposta agli obiettivi europei di neutralità climatica. La rapida crescita della domanda ha portato ad un'accelerazione della produzione che, considerando le sfide ambientali, geopolitiche e socio-tecniche, non è più sostenibile. L'introduzione di strategie di economia circolare e la garanzia di opzioni di seconda vita per i prodotti a fine vita sono le soluzioni riconosciute dall'Unione Europea. Il quadro normativo istituito negli ultimi due anni comprende requisiti e regolamenti relativi alle batterie e alle batterie usate, compresa l'introduzione del passaporto digitale del prodotto (DPP) per le batterie.

Il DPP mira a migliorare la condivisione delle informazioni, la disponibilità dei dati, la tracciabilità e la trasparenza lungo tutta la catena del valore delle batterie, memorizzando tutti gli attributi dei dati relativi alla batteria e al suo ambiente.

Questo studio sfrutta la definizione dei requisiti del DPP per le batterie per sbloccare opportunità di seconda vita combinando l'analisi normativa con un quadro decisionale. L'analisi della ricerca ha incluso un'indagine preliminare approfondita del quadro normativo pertinente e delle opportunità di seconda vita disponibili in base allo stato di salute delle batterie. L'obiettivo finale è stato perseguito attraverso lo sviluppo di una catena del valore completa a ciclo chiuso per le batterie e di un sistema di supporto decisionale (DSS) che utilizza il DPP e fonti di dati supplementari per identificare l'applicazione ottimale di seconda vita per una specifica batteria. Infine, sono stati sviluppati diversi casi d'uso lungo la catena del valore per valutare l'impatto dell'integrazione del DPP e del DSS nel perseguimento di un'economia circolare. Casi d'uso selezionati sono stati applicati al caso industriale di Envirobat España per dimostrare l'applicabilità pratica dei sistemi completi.

Parole chiave: Economia Circolare, Passaporto Digitale del Prodotto, Seconda Vita di Batterie, Sistema di Supporto Decisionale, Casi d'Uso, Rigenerazione

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1 Introduction

1.1. Thesis Structure

This thesis is structured into seven chapters (Figure 1.1).

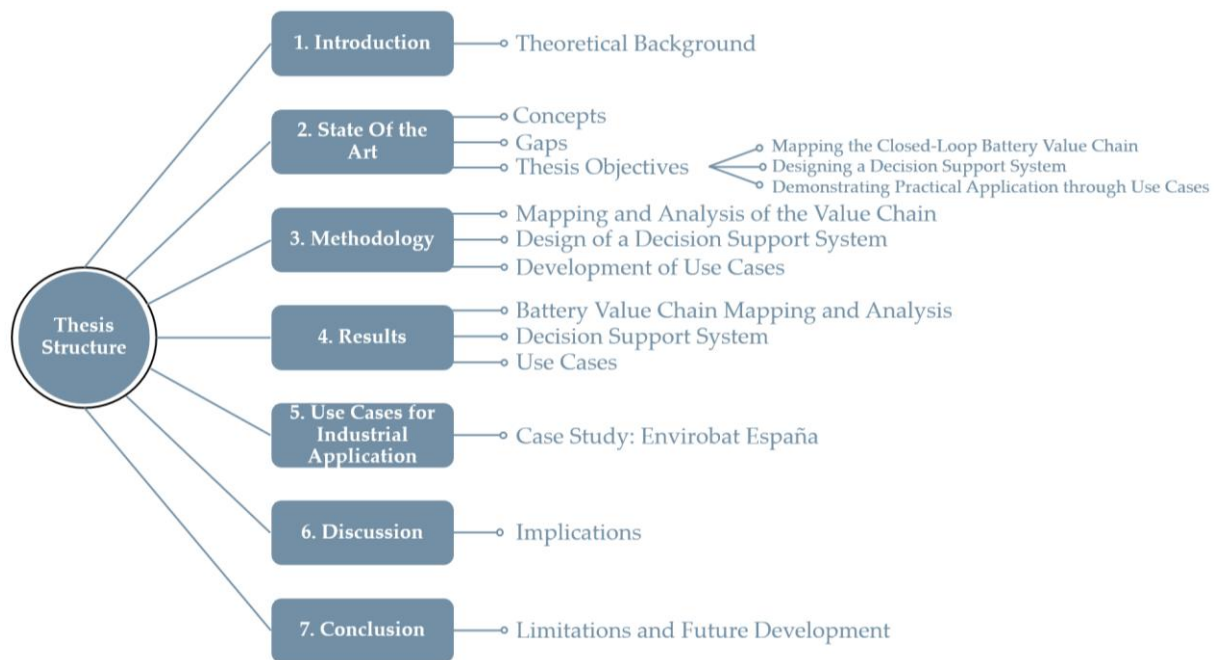


Figure 1.1: Thesis Structure

This first chapter provides an overview of the general theoretical background, with a focus on the definition of the Circular Economy and its key strategies, as well as the EV context, which serves as the starting point of this study. Both topics are described, and their main challenges are discussed.

Chapter 2 provides an analysis of the State of the Art, providing an overview of the existing regulations regarding Circular Economy, a brief background of the definitions and components regarding batteries and related technologies, the description of the Digital Product Passport, the key aspect of this thesis, and the main battery's EOL opportunities. Additionally, the thesis objectives are described, following the order of development and logic.

In Chapter 3, methodologies and tools employed to develop the results, along with their main functionalities, are described.

These three chapters represent the foundations for Chapter 4, where the results are presented and discussed in-depth with reference to the given context.

In Chapter 5 the use cases presented in the previous chapter are further analysed in a real industrial case. The selected company is Envirobat España, active in the battery recycling industry.

In Chapter 6 the results are discussed with critical thinking and a comprehensive perspective, considering the industrial point of view and the future opportunities and developments.

Lastly, Chapter 7 includes the main findings and contributions, proposing future recommendations and future developments based on the research outcomes.

1.2. Theoretical Background

1.2.1. Circular Economy

In recent years, the concept of the Circular Economy (CE) has been gaining traction because it represents the only possible solution to the growing challenges in our socio-economic world. The linear economy, the model running the current economic system, establishes that growth in demand generates growth in resource consumption, but this is no more sustainable because of several reasons; among others, the population is growing, especially in the Asia-Pacific region, causing higher resource consumption and higher Green-House Gas (GHG) emissions; additionally, the economic systems are rising, increasing the availability of products, services, and activities [1]. Another factor is the scarcity of natural resources, which has resulted from rising market demand. Human activity, based on the "take-make-dispose" system, generates a substantial amount of waste and contributes to a rise in the average global temperature, with devastating effects on both the economy and people's quality of life. [2].

As observed by the Circle Economy Foundation, this "take-make-dispose" system has led to the transgression of six out of nine global boundaries (climate change, biosphere integrity, change of the land-system, freshwater utilisation, biogeochemical flows, acidification of ocean, atmospheric aerosol loading, stratospheric ozone reduction, introduction of novel entities). Indeed, material consumption accounts for 70% of GHG emissions, while extraction and use are responsible for 90% of biodiversity loss and water stress. [1]

CE is an approach to decouple demand growth from resource consumption, without restraining economic growth, because consumption growth is less than proportional to demand growth. Therefore, the Circular Economy is a financial model that aims to optimise resource value, keep products and materials in use for as long as possible, and support the regeneration of natural systems [3]. For this reason, it is particularly

valuable in managing products with high environmental footprints, particularly during both the production and disposal phases, such as batteries [4].

Moving from a linear to a circular economy, the phases become connected, creating a closed loop in which the value is kept as long as possible, as represented in the Figure 1.2.

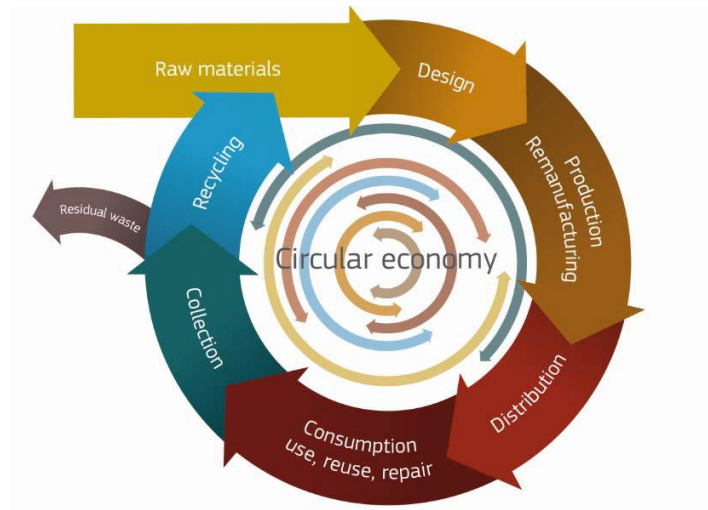


Figure 1.2: The Phases of the Circular Economy [5]

The Ellen MacArthur Foundation, a non-profit organisation dedicated to accelerating the adoption of circular economy practices, has played a significant role in advancing the circular economy. "Growth Within," which emphasises the possibility of getting more value from current products and materials rather than concentrating only on increasing flows, is the main topic covered [3].

The concept of circular economy and "Growth Within" is translated into a set of concrete strategies summarised by the Ellen MacArthur Foundation in the "butterfly diagram" (Figure 1.3).

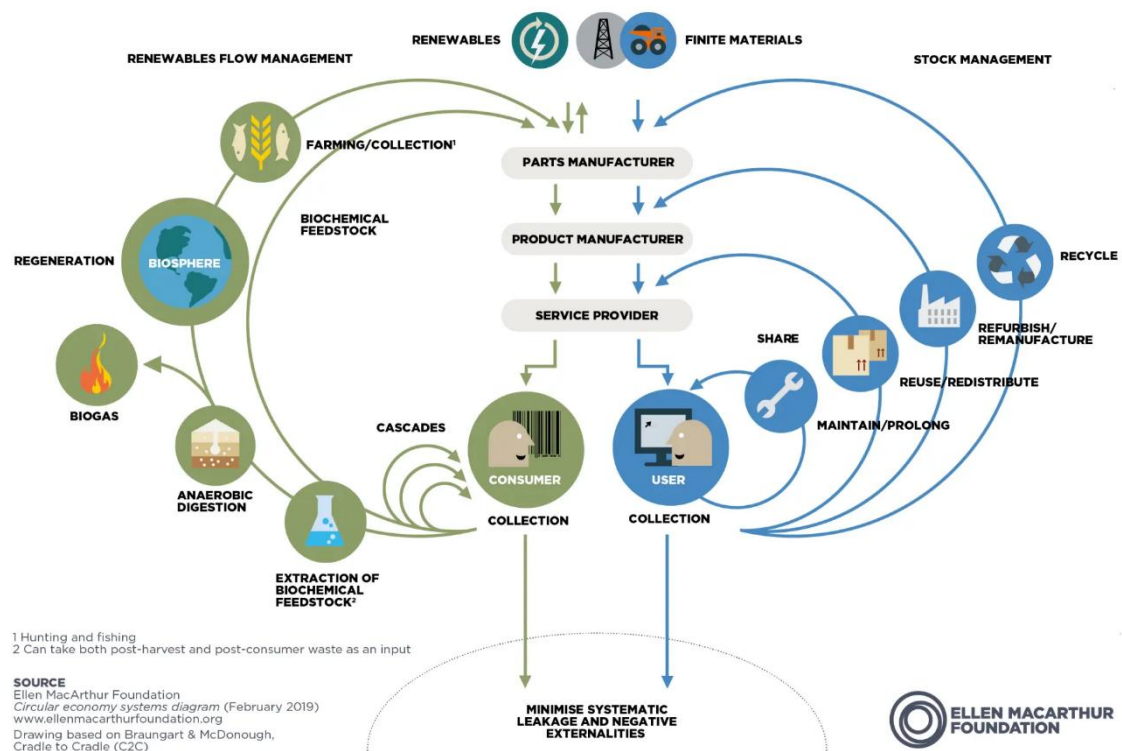


Figure 1.3: Butterfly Diagram [3]

The diagram illustrates the complexity of the CE process by showing the operators involved in diverse activities.

It is constituted of two main parts: the technical cycle and the biological cycle. In both cycles, the various loops follow a specific hierarchy from the nearest to the farthest from the user or consumer. This aspect is formalised in the concept of the “inner cycle”: inner loops can preserve more energy and value, extending product life and optimising reuse [3]. Focusing on the technical cycle, which is the subject addressed in this thesis, the primary goal is to transform products into services, thereby ensuring a longer lifecycle. This cycle is the one considered in this thesis, as it demonstrates the CE process for batteries [6].

Furthermore, the principles targeted in the diagram are further developed in the ReSOLVE framework [3]:

- Regenerate: moving to renewable energy and materials to regenerate ecosystems and biodiversity and return recovered biological sources.
- Share: maximising the products’ usage through sharing them among users (peer-to-peer sharing) and reusing them, prolonging their life with maintenance and design for durability.
- Optimise: product performance improvement and waste removal along the supply chain, leveraging big data, automation, and remote sensing.

- Loop: find opportunities and connections with other loops for upcycling or downcycling for all the components and resources of the product.
- Virtualise: deliver utility virtually.
- Exchange: replacement of old materials with advanced materials applying new technology (e.g., 3D printing) and utilising advanced products and services.

Ellen MacArthur Foundation's frameworks can be translated into another one developed by Potting et al. [7], defined as "R10 strategies". As shown in Figure 1.4, the strategies are represented in a specific hierarchy, ranging from the least to the most circular, based on their value retention potential. They are clustered into three distinct groups based on their aims. R9 and R8 relate to solid waste and correspond to the external loops of the Butterfly Model, as the product's integrity is compromised; moreover, these strategies have little influence on the production and consumption system. Actions from R7 to R3 aim to extend the lifespan of parts and components; for this reason, they require a functioning market, well-functioning reverse logistics, profitability for the actors involved, and the deployment of these strategies through varying business models. Finally, R2, R1, and R0 focus on products starting from the design phase. They are precursive strategies, as they occur before other CE strategies, enabling them to favour the other discussed strategies, and are also transformative, making the economic system truly circular if extensively applied.

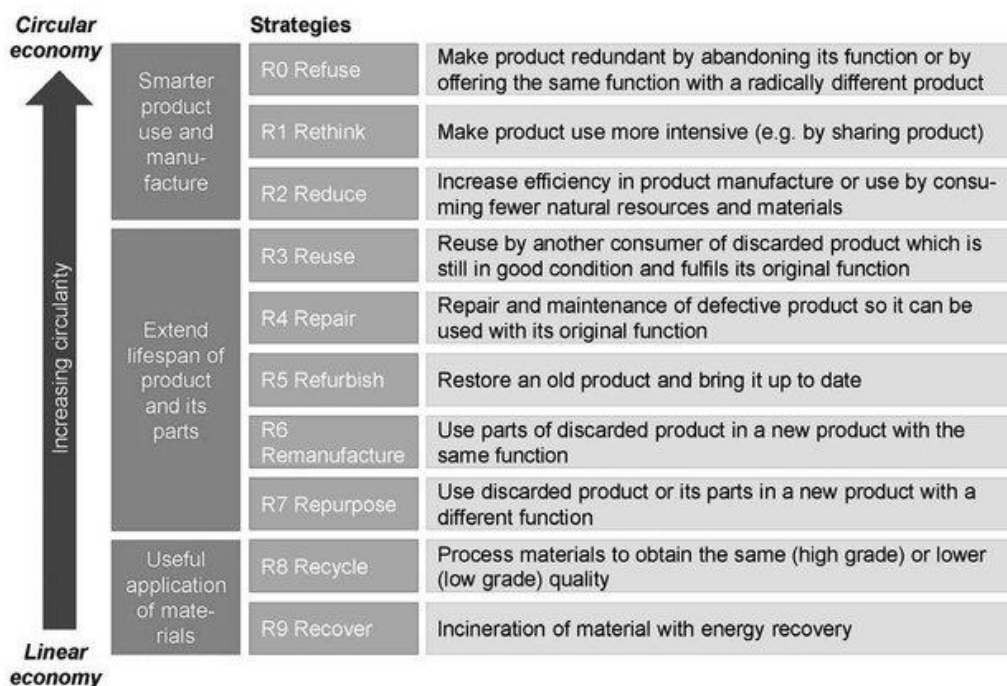


Figure 1.4: The R10 framework [8]

The presented frameworks and strategies are supported by four principles implementable at the product, service, process, and system levels [1]:

- Narrow: minimising material usage compared to linear production systems
- Slow: use longer, maximising the number of consecutive cycles

- Regenerate: uncontaminated material streams increase collection and redistribution efficiency
- Cycle: diversifying reuse across the value chain with a cascade effect, crossing companies and industry boundaries.

1.2.1.1. Challenges of Circular Economy

In practice, the implementation of CE strategies still represents a challenge for most companies, except startups and innovative companies, despite the higher interest and awareness. To prove this, as addressed in the Circularity Gap Report [1], while the amounts of secondary materials have decreased over the last five years, the majority of extracted materials entering the economy are virgin. This is reflected in the circularity rate, which decreased from 9.1% in 2018 to 7.2% in 2023. Additionally, the materials consumed globally are increasing further, expanding the distance from the defined targets.

Barriers hindering the circular transformation are complex because of the involvement of different actors at multiple levels: institution-level – lack of a clear legislative and regulatory support, supply chain-level – switch of suppliers, traceability and transparency, and firm-level – lack of organisational culture and commitment [9]. According to Hina et al. [10], barriers can be divided into internal and external. Internal barriers refer to the impediments within a company, including financial obstacles, the company's policies and strategies, technological barriers, collaborations, product design, resource limitations, and internal stakeholders. On the other hand, external barriers relate to aspects outside the firm, including consumer, legislative, economic, supply chain, social, cultural, and environmental barriers.

The low managerial commitment in companies impacts all these aspects. This happens because managers often view their interests from a medium- to short-term perspective within the company. At the same time, CE strategies are long-term, requiring a completely different mindset and the creation of a shared culture. Moreover, top executives facilitate effective relationships with all the actors involved in the value chain, acting at the system level. [11]

It is fundamental to assess how companies can effectively overcome these challenges. Theoretical studies are primarily focused on industry-specific solutions. Still, they all agree that the organisation needs to develop dynamic capabilities to face challenging times and generate a competitive advantage to adapt to the context. Franco and Giannoccaro [9] define three main dynamic capabilities to face challenges at the institutional, supply chain, and firm levels: (i) aligning the company's strategic goals to institutional opportunities and constraints, (ii) orchestrating the circular supply chain, (iii) restructuring the company to incorporate CE practices and culture.

A shift to system thinking is required to address complexity, uncertainty, trade-offs, and limit rebound effects, as the circular economy generally presents significant

challenges at both the company and system levels [1]. Nonetheless, information and communication technology (ICT)-based digitalisation has been recognised by CE researchers as a means of overcoming the many obstacles [12]. Blockchains have been recognised by Nallapanemi et al. [12] as ways to improve credibility, guarantee safe and transparent information sharing, and boost traceability—all of which are essential for successfully executing a circular transition.

Lawrenz et al. [13] define the information gap between stakeholders as the primary reason for the discrepancy between CE in the literature and in practice. For example, a user needs information on where to repair and recycle their device, or the Original Equipment Manufacturer (OEM) requires information for a suitable design. As a consequence, they emphasise the need for an information marketplace to facilitate a secure exchange of data. They represented this concept with the scheme reported in Figure 1.5: the CE product that implements CE strategies is at the centre, surrounded by all stakeholders that, during the product lifecycle, become owners of the product or its components. All of them are part of the Circular Economy, but are divided by the information gap (grey) among them.

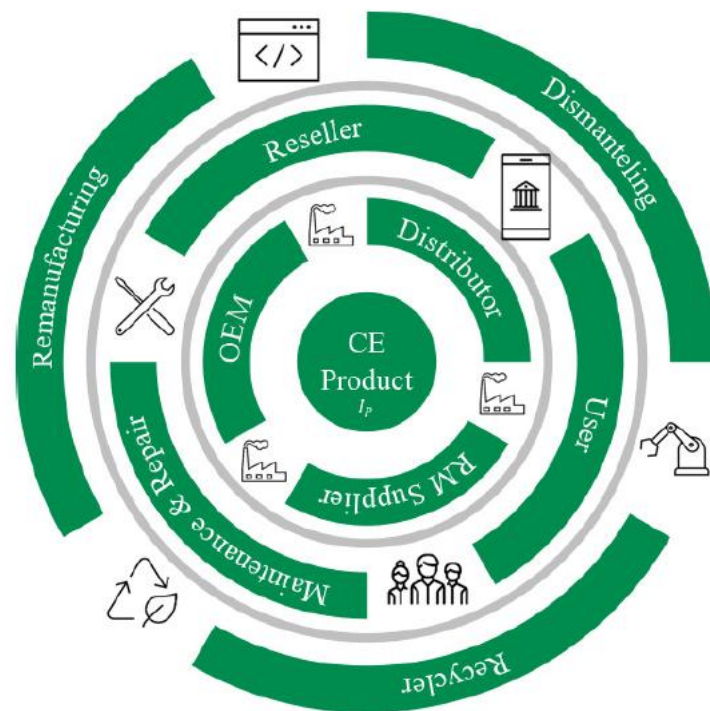


Figure 1.5: Overview about the different stakeholders in the Circular Economy and the information barriers (grey) between different layers of use [13]

Considering these insights from the literature, the Digital Product Passport (DPP) might be an effective solution to connect the different stakeholders and exchange data among them, leading to an actual transition to the circular economy [14].

1.2.2. Remanufacturing and Repurposing

As explained in the previous paragraph, several strategies can be implemented to achieve the Circular Economy.

To retain as much value as possible within the cycle, it is necessary to keep the loop as tight as possible. For this reason, and according to the waste management hierarchy [15], the recycling alternative will be considered as the last possible alternative in this thesis, despite it might be the most profitable option, especially in the case of valuable materials and the viability of recycling infrastructure.

The focus of this thesis is on remanufacturing and repurposing, as the former enables the product to be restored to functionality and appearance at least as good as a new one for the same purpose. At the same time, the latter switches to a new product, specifically in the case of batteries, by adopting a new battery management system [6]. Indeed, it is possible to utilise the product not only in the original sector, but also in new ones.

Focusing on batteries, repurposing involves utilising a battery from an Electric Vehicle (EV) whose performance is no longer sufficient for automotive use in less demanding applications. On the other hand, remanufacturing restores the battery to its original performance, making it suitable for automotive applications again.

It is essential to underline that remanufacturing in the EV context is when a pack is restored to a capacity of at least 90% while the variance in individual cell State of Health (SoH) must be a maximum of 3%, according to EU regulations [16].

The two terms are here utilised as interchangeable since, according to the regulations regarding waste batteries, remanufacturing can be considered as preparation for reuse or for repurposing [16].

1.2.3. Context: Battery Market and Challenges

In this thesis, the EV market has been considered as the overriding demand in the battery context, as it is among the ones requiring more batteries, accounting for 950 GWh or 95% of the total in 2024, with electric cars representing about 85% of the total demand [17], as observable in the Figure 1.6. Additionally, electric cars set the highest performance requirements for batteries.

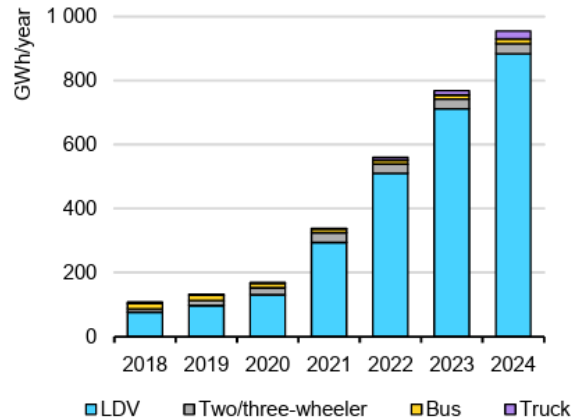


Figure 1.6: Battery demand by mode, 2018-2024 [17]

1.2.3.1. EV Market

The urgency to tackle climate change and reduce carbon emissions has accelerated the transition toward clean energy and the electrification of transportation. According to the International Energy Agency (IEA) [18], global CO_2 emissions from the transport sector grew to nearly 8 Gt CO_2 in 2022, a 3% increase from 2021, of which 40% comes from road transport. To achieve the Net Zero Emissions (NZE) Scenario, the transport sector must reduce emissions by approximately 25% by 2030.

Indeed, batteries are crucial to the decarbonization process and the shift toward zero-emission modes of transportation. Moreover, EVs contribute to the enhancement of urban air quality, resulting in a lower incidence of respiratory and cardiovascular diseases [19].

The electric car sales have registered extraordinary growth, exceeding 17 million in 2024 (Figure 1.7), rising by 25% and are expected to grow in the coming years. With over 4 million electric cars sold in the first quarter of 2025—a 35% increase over the first quarter of 2024—demand is predicted to surpass 20 million globally in 2025, accounting for more than 25% of all cars sold worldwide. Furthermore, given the current policy environment, the projections show a significant increase over the ensuing years, surpassing 40% in 2030. With the help of carbon dioxide targets, China is predicted to dominate the market, gaining an 80% sales share, followed by Europe with a share of almost 60%. [17]

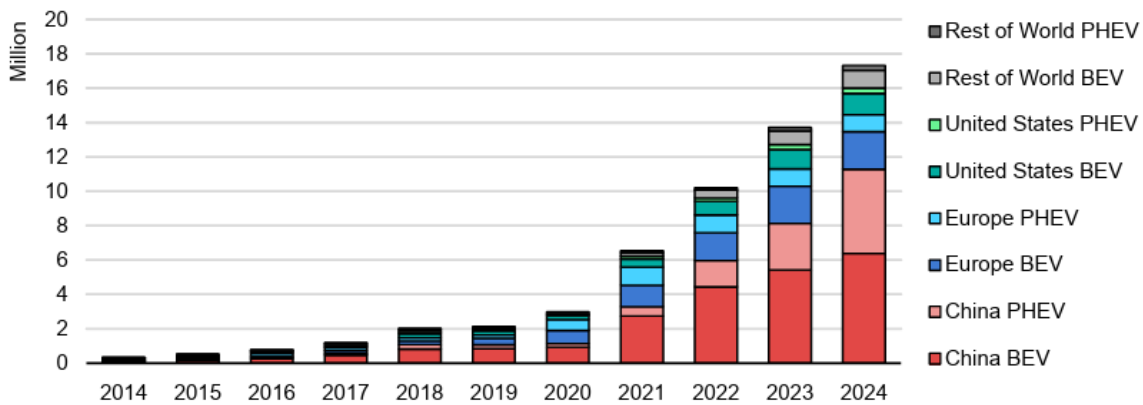


Figure 1.7: Global electric car sales, 2014-2024 [17]

Chinese growth is also driven by the competitive position given by cheaper EVs and batteries compared to the average market, and by the price competitiveness of EVs with conventional cars in the country [17].

Policies and emission standards in the European Union will require higher shares of zero-emission car sales over the next few years.

Among the various chemistries, Lithium-Ion Batteries (LIBs) are among the most widely implemented due to their high energy and power density, long lifecycle, low self-discharge rate, broad design flexibility, fast response time, high efficiency, and low maintenance requirements. Additionally, the cost has decreased over the past years.

Generally, there are five prominent families of chemical compositions in the Electric Vehicle context, which have different specific applications [20]:

- Nickel Manganese Cobalt (NMC) is composed of lithium oxide, nickel, cobalt, and aluminium. This battery is primarily used in passenger cars and light commercial vehicles, as well as in lower percentages, in heavy-duty vehicles and buses. The utilisation of this battery in these second families of vehicles is expected to rise in the current decade.
- Lithium Iron Phosphate (LFP) is composed of iron phosphate and lithium. This chemistry is primarily used in heavy-duty vehicles and buses. Still, there is an expected reduction in these applications, accompanied by a slight increase in passenger cars and light commercial vehicles. The main reason is that this battery does not contain cobalt, one of the critical raw materials for the EU. This typology, together with the precedent one, is particularly suitable for heavy-duty vehicles because it is characterised by thermal and chemical stability in case of overload and short circuit.
- Nickel Cobalt Aluminium (NCA) contains lithium oxide, nickel, cobalt, and aluminium. It is partially utilised in passenger cars and light commercial vehicles, but due to the presence of cobalt, its use is expected to decrease in the following years.
- Lithium Nickel Oxide (LNO)

- Lithium Nickel Manganese Oxide (LNMO)

The last two chemical compositions have been implemented in passenger cars and light commercial vehicles in recent periods. Indeed, they symbolise the transition to batteries richer in nickel to compensate for the cobalt shortages.

Given this description of the utilised chemistries, it is possible to deduce that future batteries will be slightly different from those that are currently commercialised. However, the shift to alternative chemistries is necessary due to the scarcity of certain materials, which could be mitigated by applying second-life strategies to the retrieved batteries. Consequently, the decision to shift to different chemistries does not reduce the importance and the results of reuse and remanufacturing applications, if well integrated with the traditional production process.

1.2.3.2. Challenges

Despite the need and benefits of transport electrification, several challenges arise.

Higher tariffs might increase the price of cars, including electric vehicles and their components, and lower oil prices affect the fuel cost savings from the use of electric cars [17]. These aspects might affect the overall car sales volumes.

Notwithstanding the rapid increase in market share over the last years, there are issues perceived from the customers' perspective. The first of these is the high price of EVs, which is primarily caused by the high cost of batteries. However, prices are currently decreasing due to the Chinese market's competitive advantage and lower battery costs. Secondly, there is widespread scepticism about whether EVs are an actual sustainable technology or merely greenwashing, considering battery production and the non-renewable energy supply required for charging. [21]

Moreover, the increasing demand for lithium-ion batteries and the limited supply of critical raw materials might cause sustainability issues and supply chain security issues [22]. According to IEA forecasts [23], the supply from current and projected mining alone is insufficient to meet demand.

Central is the critical dependence on critical raw materials and the geopolitical landscape. For this reason, the EU aims to secure critical raw materials against potential disruptions through new regulations [4]. China's predominance in supplying materials to the EU emphasises the need for a strategic plan. Another supply chain challenge is the uncertainty in the battery material demand estimations since EVs and LIBs are emerging markets, and there is a high variability in the chemistry, adoption estimations, and application parameters [24]. [25]

Battery-related emissions play a significant role in the life cycle emissions of EVs. Consequently, it is fundamental to reduce emissions related to production and critical mineral processing [26].

The main issue is what happens to batteries that reach the end of their useful life in vehicles. Indeed, the first battery's lifecycle as a traction battery in EV lasts 8-10 years, covering approximately 160,000 km or about 1000 charge-discharge cycles, resulting in a 15-20% loss in capacity [27] that makes them unsuitable for reliable use in automotive applications. In the following years, especially after 2035, when the number of end-of-life EV batteries will start growing, it will be crucial to implement R-strategies to recover materials and enhance remaining values [26].

Considering the increasing demand for EV batteries and Battery Energy Storage Systems (BESS), the quantities of End Of Life (EOL) items will rise in the next years. Kotak et al. [28] report that the number of used EV batteries available will ramp up from 50,000 in 2020 to 150 million in 2035. As a consequence, EOL strategies and standardised procedures must be implemented.

Wellten et al. [29], among the other topics addressed in the conducted interviews, report the challenges of meeting diverse requirements for niche markets, where goal conflicts occur for choices of chemistry, cell format, Battery Management System (BMS), etc. As a consequence, higher standardisation and product modularity could help manufacturers and technology owners in the development of products, shifting to an extended life perspective. In this way, it would be possible to reduce costs and decrease complexity and engineering.

Finally, batteries, especially LIB, are also used for aircraft, drones, grids, and storage, resulting in complex supply chain issues in terms of resources and EOL management [6].

1.2.4. Battery Components and Definitions

In this sub-chapter, the definitions of the main battery components, indicators, and related aspects are reported to clarify the terminology used in the following sections.

Firstly, the EV battery pack is characterised by a modular architecture (Figure 1.8) composed of cells and modules that are here defined with other essential elements and characteristics.

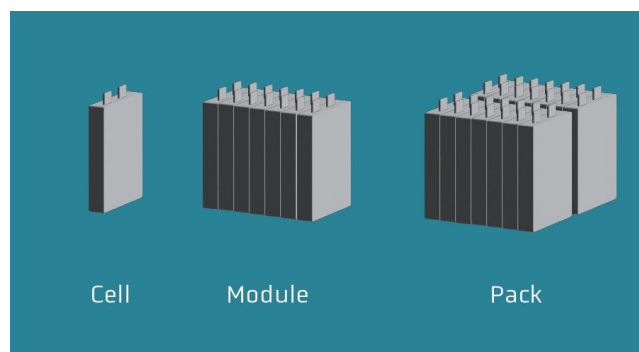


Figure 1.8: Battery modular architecture

Here is a list of characteristics that are essential to understanding this thesis.

- Battery cell: a fundamental functional unit and the main component used for energy storage. It usually consists of an electrolyte solution, a separator, and electrodes (anode and cathode) enclosed in a container with terminals. [30]
- Battery module: a set of battery cells connected or encapsulated within an outer casing for protection. Modules can be used alone or in combination with others, based on the required battery dimensions. [30]
- Battery pack: a set of cells or modules connected or encapsulated within an outer casing. [30]
- Battery Management System: an electronic system to monitor the battery through sensors placed on the battery pack. The data stored is various, such as voltage, current, and temperature, and it can compute information like SoH, State of Charge (SoC), and the remaining range for the driver [31], as established by regulators [16]. Indeed, it should allow the end-user to determine the SoH and expected lifetime at any time [16]. It must provide a software reset function, enabling economic operators involved in preparation for re-use, repurposing, or remanufacturing to install alternative software when necessary. Once this reset function is applied, the original manufacturer is exempt from liability for any safety or performance issues that arise due to the new battery management system software uploaded after the battery's initial placement on the market. [16]
- State of Health: an indicator of the battery's condition at any point of its lifecycle, utilised to determine remaining battery lifespan and reliability. It represents the battery's performance capability at a specific moment compared to its original performance capability. A new battery has an SoH equal to 100% and it decreases over time as external conditions, such as environment, usage, and recharging patterns, impact internal conditions – chemical and physical degradation. [31]
- Battery lifespan: actual time span or number of full charge and discharge cycles. [32]
- Battery degradation: the capacity fading over the lifetime of the battery. [32]

2 State Of the Art

2.1. Concepts

In this section, the relevant topics are analysed through the study of the state of the art. After an initial overview of key regulations and the Digital Product Passport, which defines the current regulatory context, battery second-life alternatives and decisions based on their performance are explained. These last concepts allow to understand how second-life opportunities can be enhanced.

2.1.1. Regulations

Achieving sustainability goals requires incorporating CE principles. Alignment with supportive policy frameworks that promote and incentivise this transition is necessary for a successful adoption, though.

To bring the rapidly expanding electric mobility industry into line with the values of sustainability, transparency, and the circular economy, the European Union has recently introduced ambitious legislation. The 2023 EU Battery Regulation, together with the Ecodesign for Sustainable Products Regulation (ESPR), establishes a new paradigm that places environmental and social considerations at the centre of industrial innovation.

The EU launched the Sustainable Products Initiative (SPI) in March 2022. This initiative included the proposal for Ecodesign for Sustainable Products Regulations (ESPR), aiming to increase the sustainability of products placed on the EU market. Indeed, consumers, the environment, and the climate can profit from more durable, reusable, repairable, and energy-efficient products. [33]

Even before the ESPR, the European Commission created the foundation of a systemic approach for circular and sustainable management of products, for instance, with the Battery Regulation in the case of batteries [34].

Despite the growing number of regulations and technical standards, several questions are still open in the literature about the import and export of second-life batteries, battery ownership, what technical standards can be applied to second-life batteries, and a few others [35].

Against this background, analysing the regulatory landscape is essential to understand not only the obligations imposed on stakeholders, but also the opportunities and risks that will define the trajectory of the EV battery industry in the years to come.

2.1.1.1. Extended Producer Responsibility (EPR)

The Extended Producer Responsibility (EPR), developed in the 1990s, is a policy approach that makes the producer responsible for their products along the entire lifecycle through a set of economic (financial and operational) tools that raise revenues and set incentives for the collection and recovery of material at the post-consumer stage. Producers must reduce the impacts of their products throughout the product lifecycle by improving design and waste management, among other actions. [36]

In financial EPR, public authorities manage product collection and recover costs from producers through service-based fees – not taxes – designed to cover net costs of waste collection and treatment, encourage ecodesign among Producer Organisations (PROs), support recycling, and fund awareness campaigns. [36]

In operational EPR, producers are directly responsible for setting up and managing waste collection and recovery, as well as covering all related costs. Their obligations are usually linked to performance goals such as collection, recycling, or reuse rates. Although producers can implement EPR obligations individually, they usually collaborate through PROs. [36]

After decades of implementing the EPR, it is possible to state that, if done correctly, it enhances transparency, mobilises significant financial resources, and increases the collection and material recovery rates of targeted products. Moreover, it can incentivise design change and reduce the use of primary virgin materials. [36]

Mallick et al. [37] target the need for policymakers and manufacturers to transition EPR from a simple waste management strategy to an “interface policy” that covers the interdisciplinary areas of circular economy, chemical, and waste law.

Finally, Gupt and Sahay [38] discuss the dependency of EPR on a strong regulatory framework for upstream management with well-defined stakeholder roles and producer obligations. Producers are supposed to take on the financial burden while assigning specialised organisations, such as PROs, to handle the actual collection and recycling duties to ensure higher rates of resource recovery, recycling, and collection. To ensure success, regulations and upstream activities must be closely monitored and managed. Fines should be imposed for noncompliance, and financial incentives should be provided to all parties. Additionally, EPR initiatives are most effective when combined with other complementary policy instruments, such as landfill taxes. Strong EPR models, particularly for developing countries, can be developed with the aid of these insights.

2.1.1.2. European Green Deal (EGD)

The European Green Deal, introduced in 2019, is a European strategy for growth through policy initiatives focused on a green transition, with the aim of achieving climate neutrality by 2050. This plan emphasises the importance of policy implementation across various economic sectors, including energy and agriculture. [2]

The recommendations of this strategy have been transformed into laws and regulations applied across all EU member states.

This document doesn't have the only goal of reaching climate neutrality, but also others: the implementation of circular economy as a new economic model, clean industry to increase sustainability and energy efficiency in production systems, climate justice and fairness to make this transition equitable and inclusive, a healthier environment to strive for zero pollution, and more sustainable farming to safeguard the environment and provide wholesome and reasonably priced food. [2]

Due to the legal obligations of EU nations resulting from the 2015 international treaty known as the Paris Agreement on Climate Change, climate neutrality is essential. During the first meeting, governments agreed on the need for a community effort to limit global warming below 1,5°C. The agreement took effect in November 2016, after the requirement was fulfilled that at least 55 countries, responsible for at least 55% of global greenhouse gas emissions, had been met (Fit for 55). [2]

Additionally, the circular economy is a key aspect of this document, which is broadly discussed in the Circular Economy Action Plan, one of the main building blocks of the EGD.

This document presents a comprehensive strategy for achieving climate neutrality, but it doesn't come without criticalities and concerns that have been addressed in the literature.

Da Silva Hyldmo et al. [39] highlight a core contradiction on which the European Green Deal is structured. While it makes the ambitious claim about achieving a "just and inclusive transition" to a low-carbon economy, its implementation relies on a massive extraction of raw materials and a massive increase in demand for electrification and digitalisation. Most of these materials are sourced from the Global South, where the most marginalised populations feel significant negative ecological and social impacts. They state, consequently, that the constructed narrative of the EGD is demarcated within the EU, without accounting for external impacts. These contradictions and inconsistencies might undermine the European logic and legitimacy.

Furthermore, Hereu-Morales et al. [40] cast doubt on the Green Deal's viability and come to the conclusion that the EGD's plans do not match its claims of being a revolutionary master plan for sustainability because of two key problems. First, it prioritises economic growth, frequently at the expense of environmental concerns. This can put efforts on sustainable development issues that aren't directly related to the economy at risk and worsen environmental degradation. Secondly, it simplifies complex sustainability concepts, such as climate neutrality, the transition to renewable energy, the circular economy, and sustainable raw material extraction.

2.1.1.3. Circular Economy Action Plan

The Circular Economy Action Plan was presented in 2020, as part of the European Green Deal, to target 30 action points about waste reduction, development of sustainable products and circularity in production processes, consumer awareness, and key sectors targeting [41].

Indeed, the document outlines several circular actions, including ecodesign, as further addressed in the ESPR, and the “right to repair” to promote repair over replacement.

As mentioned, the Action Plan identifies key sectors as the most resource-intensive ones, but with high potential for circularity. Among them is the battery and waste battery sector, highlighting the need for a circular economy to be created throughout the entire life cycle, especially given the massive adoption of electric vehicles.

The other addressed sectors are electronics and ICT, textiles, construction and buildings, packaging, and plastics. Unsurprisingly, many of these are among the first to require a DPP.

2.1.1.4. End-of-Life Vehicles (ELV) Directive

This directive was first introduced in 2000 to address the automotive industry, one of the industries with the highest consumption of raw materials. Despite the high recycling rates of materials from this sector, the scrap metal produced is characterised by low quality, and only small amounts of plastic are recycled. Indeed, it sets targets for ELVs and their components, and prohibits the use of hazardous substances during the manufacturing of new vehicles. The ultimate objective is to prevent and minimise waste from the automotive industry and to enhance the environmental performance of economic operators involved in this sector. [42]

The regulation was reviewed in 2023 to align it with the EGD and the Circular Economy Action Plan. Therefore, it now includes additional aspects related to circularity and end-of-life treatments; to cite some of them: circular design improvements to facilitate removal of materials, parts and components, recover more and better-quality materials, increase inspections, and cover a broader range of vehicles [42]

In this way, the extended producer responsibility and improved measures for dismantling, reusing and recycling vehicle components are now part of the directive [43].

However, Lin et al. [4], interviewing stakeholders in the automotive sector, revealed some concerns about the regulations. Notably, respondents highlighted some economic challenges associated with battery repurposing, especially in terms of costs, and they noted that technical complexities introduce additional engineering steps. Moreover, according to interviewees, overlapping frameworks, including the ELV

Directive, create further complications, as battery removal is restricted to a qualified disassembler, adding procedural and compliance-related challenges.

2.1.1.5. Ecodesign for Sustainable Product Regulation (ESPR)

The Ecodesign for Sustainable Product Regulation (ESPR), which came into effect in 2024 as part of the 2020 Circular Economy Action Plan, contains the directives of the European Commission to increase environmental sustainability and product circularity [44]. This document serves as a framework that does not establish specific measures but rather enables their later adoption. As a consequence, it can help the EU achieve the environmental and climate goals set for the upcoming years.

The ultimate goal is to establish a European single market for sustainable products, leveraging circular requirements such as extended durability, reusability, repairability, and resource reduction. The existence of this market enables the environmental, social, and economic facets of the triple bottom line to become more sustainable. In fact, in addition to promoting environmental sustainability, the circular economy would also create new job opportunities and economic benefits, such as through recycling and maintenance. [44]

Since product information is essential to boosting traceability and circularity, the Digital Product Passport is one of the main topics covered in the ESPR. The European Commission has identified a framework for its implementation across various sectors. It is interesting to notice that the first product to have a regulated DPP is the battery, followed by textile, electronic, and construction products. Initially applicable to energy-related products, it now covers virtually all products, except for food and feed, and medicinal products. Based on each product's impact assessment, the measures listed are specific to that product. [44]

To prevent trade disruptions and the emergence of a global "two-speed market" for sustainable products, effective regulatory cooperation is crucial. The EU is now faced with a critical decision: either it can establish itself as a global leader by establishing the standard for sustainable products, or it runs the risk of expanding regulatory differences with other regions, which would result in markets that are fragmented and less effective. Despite its pledge to raise sustainability standards, it actually faces the risk of imposing trade restrictions that could affect countries with less robust institutional frameworks. [45]

Bundgaard et al. [46] emphasise how crucial it is to take into account the knowledge and insights gained from the previous Ecodesign Directive. It is essential to create additional approaches that are suited to new product categories while maintaining strong, context-specific requirements. Strengthening the emphasis on the circular economy's "inner circles" is equally essential in order to preserve product value for as long as feasible. At the same time, the increased complexity of products and potential trade-offs call for a comprehensive and standardised framework to assess material

efficiency in future preparatory studies. Finally, synergies already established between performance and information requirements under the Ecodesign Directive and EU Energy Labelling schemes could serve as a model for material efficiency indicators in the ESPR, such as repairability and durability indexes.

2.1.1.6. EU Battery Regulation (Regulation 2023/1542)

This regulation, adopted by the European Council on 14 June 2023, focuses on sustainable rules for batteries along the entire lifecycle, from production to reuse and recycling. This regulation is revolutionary, as it is the first to address a product throughout its whole life cycle, representing a product-specific delegated act.

The ultimate goal is to enhance the competitiveness of European industries and ensure the development of sustainable new batteries, thereby limiting the reliance on third countries, such as China. Indeed, the new rules improve the functioning of the battery's internal market through safety, sustainability, and labelling requirements, introducing the Battery Passport. [47]

Three main problem groups are targeted. Firstly, it addresses the lack of incentives for sustainable battery production by presenting clear guidelines and encouraging investments in environmentally responsible technologies. Secondly, the regulation targets suboptimal recycling and material loops, aiming to close the gap in recycling markets and establish comprehensive rules for sustainable recycling practices. Finally, it mitigates uncovered social and environmental risks by introducing transparency requirements, regulating hazardous substances, and promoting strategies to neutralise the environmental and social impacts of battery lifecycles. [4]

The regulation will apply to all batteries and establishes end-of-life requirements, including collection targets, material recovery targets, recycling efficiency targets, minimum levels of recycled content, and extended producer responsibility. Additionally, the regulation defines due diligence rules for operators to reduce social impacts [47].

The scope concerns all categories of batteries (portable, starting, lighting and ignition, light means of transport (LMT), electric vehicle, and industrial batteries), regardless of their characteristics or whether they are incorporated into other products [16]. Moreover, it also applies to batteries subjected to reuse, repurposing, or remanufacturing, covering the whole lifecycle. As a matter of fact, batteries in LMT, industrial batteries with a capacity above 2 kWh, and EV batteries placed or put into service on the EU market (Article 77, 1) [16], must be connected with a battery passport from 18 February 2027. The regulation also maintains a total prohibition on landfilling waste batteries. All waste batteries must be collected by Economic Operators free of charge for end users, regardless of the nature, chemical composition, state, brand, or origin of the waste battery in question [35].

As inferred by this depiction of the regulation, it is clear that it addresses the issues left open in the ESPR regarding batteries, with a particular focus on the content of information to be stored in the DPP.

Among researchers, concerns exist about the incentives involved in sourcing recycled materials. Indeed, authors are concerned that, in order to meet recycling targets, reuse and second-life strategies may be overlooked, resulting in premature recycling, often due to economic considerations. This issue is concrete and in conflict with the EU waste hierarchy itself. [48]

Furthermore, some authors draw attention to the potential ambiguity surrounding the circumstances under which the producer may transfer responsibility, which could lead to responsibility evasion. As a result, producers or OEMs might attempt to transfer their disposal duties to outside operators who lack the necessary infrastructure or capability to manage waste in an environmentally friendly manner. Additionally, inconsistent battery waste management can undermine recycling procedures and compromise environmental sustainability due to a lack of proper regulatory oversight. [35]

2.1.2. Digital Product Passport

As mentioned in the previous sections, the Digital Product Passport is a key aspect of European regulations. This passport is a digital document recording the production, the usage history, and relevant information of the product to enhance traceability and compliance along the product lifecycle, but also to increase sustainability, circularity, value retention for second-life, and compliance along the value chain [31].

As explained in the Chapter 2.1.1.6, it has been formalised in the EU Battery Regulation, in line with ESPR objectives.

Complex obstacles, such as a persistent gap between the need for more data and inadequate data sharing practices across supply chains, deter many manufacturing companies from fully embracing circular transformation. As a result, players in a circular supply chain are unable to access the product life cycle information they need. DPPs are suggested as a solution because they serve as a mechanism for storing product data and information, enabling different supply chain participants to add and retrieve pertinent data. [49]

As a matter of fact, the DPP represents a digital twin of the physical product that transports the information about the whole lifecycle and its interactions [43].

The Digital Battery Passport focuses on providing unique life cycle data. There are four key battery traceability characteristics of the shared data: provenance through tracking and tracing, uniqueness through an individual identification number, trustworthiness of the data shared among the actors, and battery configurability [50]. Since it tracks the product throughout its entire lifecycle and simultaneously tracks the product's

materials from their point of origin through EOL and back into the supply chain, it is in fact related to the "Track and Trace" (T&T) approaches [43]. It is also a crucial instrument for increasing material recovery, reducing recycling expenses, and enhancing transparency [25].

It can support circular battery management practices, such as prolonging battery life, enhancing reuse and remanufacturing capabilities, and streamlining recycling procedures, by increasing material transparency and traceability [51].

The data included in the DPP is both mandatory and voluntary, based on regulations and specifications, and must be dynamic so that it can be updated during the product usage and reflect the up-to-date battery status. It is a structured set of mandatory and non-mandatory machine-readable and product-related data exchanged through a digital infrastructure.

A further in-depth discussion about DPP's content data and requirements is proposed in the Chapter 2.1.2.4.

The DPP system's architecture is a secure, modular, and interoperable framework that facilitates the standard exchange of product-related data throughout the value chain. The product identifier, the EU-managed registry, and decentralised data sources operated by economic operators are all connected by a layered structure that defines the basis of the technical design. Every physical battery (or other regulated product) can be clearly linked to its digital passport thanks to the Unique Product Identifier (UID), which acts like the key to access distributed information stored in databases and knowledge graphs. To ensure a continuous and traceable information flow throughout the product lifecycle, the architecture is designed to support both static data attributes (manufacturing information, composition, and compliance declarations) and dynamic attributes (performance updates, SoH, and usage history). [52]

DPPs can have local (requiring physical proximity, e.g., RFID tag), cloud-based (accessible from anywhere), or hybrid connectivity (combining local and cloud instances) [53].

From the system's point of view, this architecture combines central oversight with decentralised data storage. By enabling information to be accessed through the UID without the need for a single central database, standardised data models promote interoperability. This strategy mitigates the risks of data monopolies, safeguards privacy, and ensures compliance with data sovereignty standards. In addition to facilitating the implementation of other features, such as cross-sector data aggregation, traceability audits, and lifecycle impact assessments, the architecture is designed to integrate other product categories. In summary, the DPP system architecture offers a hybrid model that includes interoperable standards for machine-readable carriers and data exchange, a decentralised data infrastructure run by economic operators, and a globally unique identification framework connected to the EU registry. In addition to

offering the technical underpinnings for circular economy principles and regulatory enforcement in the European market, this guarantees the system's transparency, traceability, and long-term resilience. [52]

As a result, the decentralised approach, which improves data security, resilience, and robustness, defines the DPP system architecture. Moreover, it enables the allocation of responsibility to the appropriate stakeholders, distributing the system load efficiently. The decentralisation feature enables the interaction of many actors and services, a fundamental aspect in the current environment that permits the evolution of an ecosystem of information, as every participant can freely contract with the others [52].

Despite the benefits and its vast potential, Pohlmann et al. [51] underline that the DPP use does not automatically result in greater sustainability and circularity because it must be adequately managed. Collaboration and information sharing between actors are essential for the successful realisation of circularity. Standardisation and interoperability, data privacy and security, stakeholder resistance, integration complexity, and cost implications are some of the other obstacles to its implementation [53]. Effectively attaining transparency, efficiency, and sustainability requires overcoming these obstacles.

2.1.2.1. CIRPASS-2

CIRPASS-2 is an Innovation Action project founded by the European Commission's Digital Europe Program based on a broad consortium of organisations (49 partners) from industry, research, digital technology, and standardisation organisations across Europe. The outcomes of the CIRPASS (Collaborative Initiative for a Standard-based Digital Product Passport) project, which ended in March 2024, served as the foundation for CIRPASS-2. This initial project created roadmaps for prototypes in three value chains—textiles, electronics, and batteries—and set the foundation for the DPP's gradual development. CIRPASS aimed to establish a preliminary methodological and technological infrastructure by defining key attributes, interoperability standards, and governance models for data management and traceability along value chains.

The project aims to demonstrate the functioning of DPPs in real-world settings and at a large scale across four target sectors: textiles, electrical equipment, tyres, and construction materials. Moreover, it develops cross-sector standards and frameworks.

Both are key reference points in the European landscape for fostering sustainability, a circular economy, and transparency through products' DPPs.

2.1.2.2. Battery Pass

Battery Pass is a consortium of 11 partners from industry, science, technology, and beyond, cofounded by the German Federal Ministry of Economic Affairs and Climate Action (BMWK) and led by system change company SYSTEMIQ GmbH, with the

intention of offering advice regarding the EU Battery Passport. Project management, stakeholder engagement, content requirements, technical battery passport system guidance, software development, physical demonstrator, and value assessment of individual use cases and system benefits are all included [54]. It also maintains and works with CIRPASS projects, guaranteeing standardisation.

During the project, the consortium is establishing a detailed perspective on content requirements for the battery passport, identifying necessary and evaluating existing standards for the technical infrastructure, developing software and physical demonstrators, and assessing the value of the battery passport for companies, societies, and the environment [34].

2.1.2.3. Battery Actors

The Battery Pass Consortium [34] outlines an overview, considering various regulatory frameworks, especially the EU Battery Regulation [16], of the actors involved in the battery handling stages. It is essential to be aware that the presented actors are not separate by definition, but a single company can cover diverse roles. Indeed, this representation does not depict actors per se, but rather the roles they carry out. These roles are alphabetically listed below:

- **Authorised representative:** any person who has received a mandate from a manufacturer to act on its behalf on tasks regarding the manufacturer's obligations.
- **Distributor:** any person in the supply chain who makes a battery available on the market.
- **Economic operator:** any natural or legal person subjected to obligations related to the manufacture, preparation for reuse, repurposing, or remanufacturing, the making available, or placing the batteries on the market.
- **End-user:** any person residing or established in the EU, to whom a battery has been made available as a consumer or as a professional end-user.
- **Holder of a battery:** the person in possession of a used or waste battery.
- **Importer:** any person within the EU who places a battery from a third country on the market.
- **Independent operator:** a person independent from the manufacturer and producer who is involved in the repair, maintenance, or repurposing. It includes waste management operators, repairers, manufacturers or distributors of repair equipment, tools, or spare parts, publishers of technical information, testing operators, trainers, and others.
- **Person with a legitimate interest:** anyone with a legitimate interest in accessing and processing battery passport information.
- **Manufacturer:** any person who manufactures a battery or has a battery designed or manufactured and puts it on the market under their own name or trademark.

- National authority: an approval authority implicated in and responsible for market surveillance in a Member State. In the described environment, the authority must be seen as a market authority, with the role of checking the data and information flow, without acting as a central control point.
- Producer: any manufacturer, importer, or distributor that manufactures batteries under its name or trademark, resells within a Member State, sells batteries, or supplies for the first time in a specific Member State.
- Producer responsibility organisation: a legal entity that financially (and operationally) organises the fulfilment of EPR obligations.
- Recycler: any person who carries out recycling in a permitted facility.
- Waste holder: the waste producer or the person in possession of the waste.
- Waste management operator: any person dealing with the separate collection, treatment, or recycling of waste batteries.

Identifying these roles is fundamental to defining responsibilities throughout the DPP creation and access process. On the other hand, the possible overlap and intersection of roles may cause uncertainty in the subdivision of obligations, potentially resulting in a lack of data or duplicates in the data collection.

Psarommatis and May [53] identify a total of seven actors: OEM, end user, maintenance, distributor, value chain partner, recycler, and DPP data analyser. Additionally, they explain that the OEM is both the owner and creator of the DPP, while the distributor's role is to bring the product to market; hence, its responsibilities differ from those of the OEM. All other actors are responsible for retrieving or adding data types to the DPP based on the occurrence when the product is in their possession (Figure 2.1), so the creator and manager must grant the correct data access.

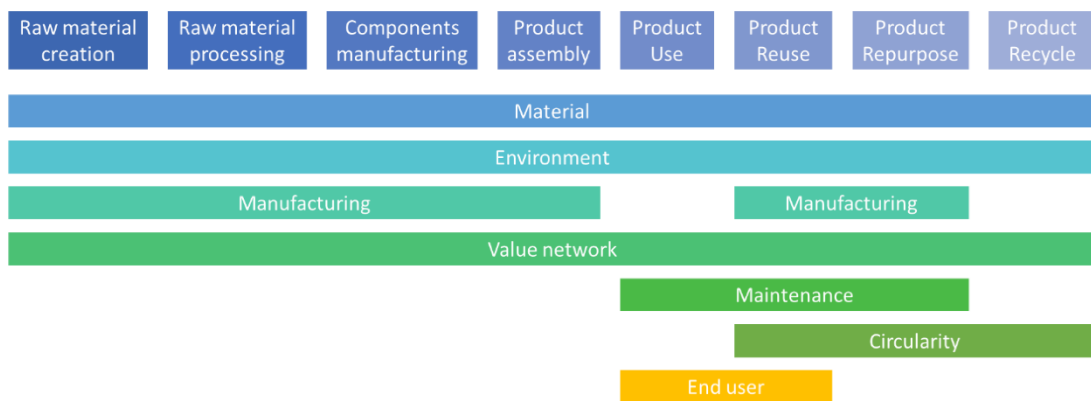


Figure 2.1: Timing at which the different types of data in DPPs are generated [53]

2.1.2.4. Digital Battery Passport Content

In earlier chapters, it was emphasised how crucial the data in the Digital Battery Passport (DBP) is for improving second-life opportunities and addressing various value chain participants. All of the information contained in the passport must be reliable in order for this to occur; in fact, the right person must write the right

information at the right time, as stated in the Regulation: the information must be "accurate, complete, and up to date." (Article 77, 4) [16]. To show that data is accurate and correct, the writer should specify what the requirement is for a specific attribute and how it can be determined.

The DPP information content is defined by regulations and requirements for the battery sector, whereas it is still in development when referring to textiles and electronics. Particularly, the detailed content is provided by the Battery Pass Consortium in the "Battery Passport Content Guidance" [34], built on the EU Battery Regulation, the ESPR, the EU Critical Raw Materials Act, the EU Corporate Sustainability Reporting Directive (CSRD), and other relevant regulatory frameworks to generate additional background information and synthesise reporting requirements.

The data attributes are outlined by the European Union in the EU Battery Regulation [16] and grouped into seven clusters by the Battery Pass Consortium [34] as noticeable in the Figure 2.2.

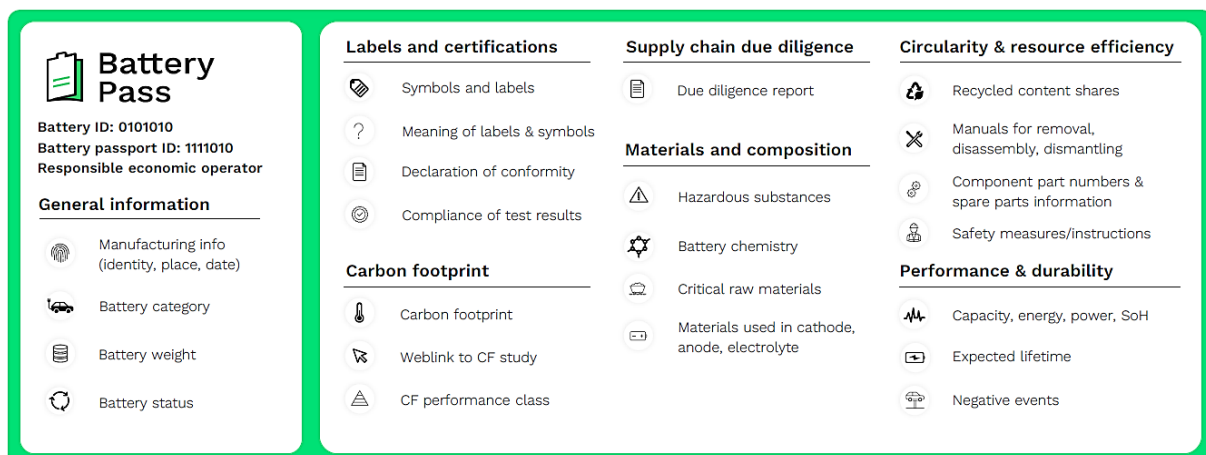


Figure 2.2: Data categories for the battery passport [54]

The clusters have been slightly modified in a more recent standard DIN DKE SPEC 99100 [55], developed by the Battery Pass Consortium in cooperation with public industry consultation and based on the "Content Guidance for the EU Battery Passport" documents. Particularly, the first category, "general information," has now been renamed to "identifiers and product data", "labels and certifications" to "symbols, labels and documentation of conformity", and some attributes have been modified, added, or updated in all clusters.

Analysing the single attribute categories, the first one, "identifiers and product data," includes identification aspects such as the battery passport, battery identifier, manufacturer, operator identifier, and associated information. Additionally, it contains battery data and characteristics, including battery category, mass, and status, as well as the manufacturing date and place, and the warranty period of the battery.

Moving to “symbols, labels and documentation of conformity”, it contains mandatory symbols and relevant compliance documents. With a similar purpose, the category “supply chain due diligence” stores information on due diligence reports, third-party assurances, and supply chain indices, including details about social and environmental supply chain matters. Moreover, the cluster “battery carbon footprint” refers to the environmental accountability in terms of carbon footprint. The standard highlights that the carbon footprint must be defined per functional unit of the battery, as declared in the battery carbon footprint declaration, posing an additional guideline in the computation [34], [55].

The product’s circularity is further addressed by the last two categories: “battery materials and composition” and “circularity and resource efficiency”. The former comprises attributes related to the presence of critical raw materials and hazardous substances, as well as the battery chemistry and materials used, along with their environmental, health, and safety impacts. The latter focuses on useful circular economy indicators, as well as information about battery disassembly and guidelines for waste management. In particular, it contains information about the sources of spare parts, how to use them, how to prevent waste, how to prepare for second life, and how much content is recycled.

The last and most comprehensive category is “performance and durability,” which includes details on battery life, temperature, unfavourable occurrences, capacity, energy and voltage, internal resistance, and power capability. This cluster is important because it offers timely and accurate information that aids in technical assessment and decision-making.

These data categories can be static, as provided when the battery is placed on the market. They may change in the event of part replacement or BMS replacement. Otherwise, they can be dynamic, expected to change regularly during battery usage. The former includes general information, materials, and composition, as well as carbon footprint and pre-use performance data attributes. The latter can be monitored by the BMS or uploaded manually, as in the case of accidents. [34]

Dynamic data attributes are fundamental to tracking the changes the product has undergone during its life; for this reason, an effective integration and connection between the specific product’s DBP and BMS is imperative.

The clusters proposed by the Battery Pass Consortium are generally aligned with those identified and proposed in recent academic literature research.

Berger et al. [56] They were the first to define the battery passport in terms of information needs and requirements, identifying four main information categories: battery (product identification and contextualization), sustainability and circularity, diagnosis, maintenance, and performance, as well as value chain actors.

Furthermore, Stratmann et al. [57] identified four categories of attributes that should be contained in the DPP: “Product Information”, “Utilisation Information”, “Value Chain Information”, and “Sustainability Information”. These categories are pretty aligned with the attribute requirements defined by the Battery Pass Consortium, even though the authors’ proposal is more general and related to the whole manufacturing industry, not a specific sector. The main difference regards “System Information”, a sub-category of “Product Information” that includes software information, digital interfaces, and add-ons. These aspects do not seem to be included in the longlist attributes proposed for batteries [58]. Jensen et al. [49] identified seven data clusters: usage and maintenance, product identification, products and materials, guidelines and manuals, supply chain and reverse logistics, environmental data, and compliance, which are all aligned, except for the supply chain and reverse logistics, with the attribute requirements.

According to a report developed by the World Economic Forum [43], it is recommended that additional metrics be included. In particular, incorporating the energy delivered throughout the lifetime of a product or estimating the carbon footprint of a battery per unit of energy delivered might encourage designers to define batteries characterised by longer lifespans, considering both first- and second-life applications.

Additionally, tracking data such as performance and durability, carbon footprint, and energy delivered, allows automakers to choose more sustainable batteries to meet the required performance needs, while contributing to the company’s sustainability and emission goals [43].

According to a study done by Wellten et al. [29] interviewing companies in a global Electric Vehicle Battery (EVB) supply chain, the interviewee identified seven categories of data preferences: battery status information, product specifications, product location, complete history, sustainability and circularity-related information, safety information, and ecosystem actor-related information. All these categories can be provided by the Battery Passport if the requirements are well set and followed, and the integration with the BMS is effective.

Pohlmann et al. [51] identified, through surveys, the most critical attributes for diverse actors along the value chain. For post-use actors, the most relevant information is: State of Health, product-related energy, power capability, rated capacity, and the long-term trend of the State of Health. On the other hand, for beginning-of-life actors, recycling information, dismantling instructions, specifications of electrodes, as well as the State of Health, are considered fundamental. Lastly, the EOL actors viewed the electrode specification, recycling information, disassembly instructions, and module and cell specifications as the most critical elements. [51]

However, Rufino et al. [35] emphasise that there is a lack of clarity surrounding the precise mandatory data that businesses must reveal in order to ensure the

sustainability and circularity of batteries. Additionally, it's unclear what information needs to be reported to address problems like battery tampering and tax evasion. In addition, certain types of data may only be submitted voluntarily, for example, to support the creation of digital twins or to validate projects during their initial development phases [35].

Another possible issue regards the BMS integration with the DPP: OEMs are generally reluctant to disclose BMS data publicly; therefore, legislation should guarantee that their technological expertise and proprietary knowledge remain protected [35].

Several other studies regarding DPP's content issues have been published in recent years, but are not considered, given that the content attributes have been updated in the current year. For this reason, they might not be reliable.

Anyway, the Consortium's guidelines should be set as a new starting point for further research in the future. Additionally, the battery passport guidelines set the foundation for structured and standardised DPPs in other contexts that have not yet been in-depth analysed and defined.

2.1.3. Battery's Second-Life Opportunities

As mentioned above, the market penetration of EVs generates the need for the extension of the batteries' potential value. End-of-life batteries contain many valuable resources, and it is fundamental to reuse the critical raw materials contained in the batteries instead of relying on third countries for supplies. Furthermore, batteries retain roughly 80% of their initial capacity when their initial useful life as traction batteries in the automotive industry comes to an end [27], which presents a relevant opportunity for alternative applications. Long-lasting chemistries combined with eco-driving, which enhances the battery's environmental performance through reuse and repurposing, could further improve this aspect [59]. In fact, driving habits, usage patterns, charging and discharging behaviour, technical specifications, design decisions, and climate all affect the tipping point, which is 80% of the initial capacity [29].

In addition to improving sustainability in the energy and transportation sectors, this approach helps to reduce environmental waste from premature disposal [60] and lowers greenhouse gas emissions related to the production of lithium-ion batteries by 30% when compared to a single-use lifecycle. [61]. Moreover, it can offer cost-effective solutions that ease the transition to a low-carbon energy infrastructure [61]. For example, second-life batteries (SLB) can perform effectively in stationary storage systems for 7-10 years more [60]. Additionally, SLB reuse and refurbishment can decrease EV costs as well [21] and benefit EVs' reputation as "zero-emission" vehicles in terms of charging sources [62].

A key challenge of second-life strategies is the battery heterogeneity in terms of models, forms, chemistry, brand, and electric characteristics, among others; however,

the future selling rates are expected to decrease the need for multiple EV battery adaptations. According to Kotak et al. [28] SLBs should be installed in small- to medium-scale applications to minimise this variability: since EV batteries had an average energy capacity of 44 kWh in 2019, while the largest capacity is now around 100 kWh, more than one battery would be necessary for most applications to meet energy requirements. As a consequence, design and technology choices within types of cells, chemistry, modules, packs, and battery systems are critical to enabling second-life strategies. [29]

Lin et al. [4] identify additional barriers to batteries' second life: safety and warranty issues are of primary concern, considering that end-users are apprehensive about the performance reliability of repurposed batteries. Moreover, the current limited access to data prevents conducting safety tests and compatibility checks for second-life applications [4].

Finally, barriers can be at a high level as well: an effective battery reuse requires inter- and intra-industry partnerships [62].

Kotak et al. [28] state that some of these challenges can be faced by considering different options: the module dismantling allows for a versatile solution, capable of going from small to large systems, and the dismantling into cells maximises the versatility and reduces inhomogeneity of the resulting battery, since a cell selection according to their SoH is feasible. On the other hand, the cost increases because of higher manipulation, testing, and the need to implement new control systems at the cell, module, and pack levels.

In the 1990s, the literature started investigating the application of EOL batteries in less demanding applications, especially BESS, where a lower energy-to-weight or volume ratio is not a significant issue [60], [63]. In this way, it is possible to prolong the product's lifetime, delaying waste generation.

On the other hand, large-scale industrialisation began only in the 2010s when automakers and battery manufacturers launched some projects accessible in the Figure 2.3.

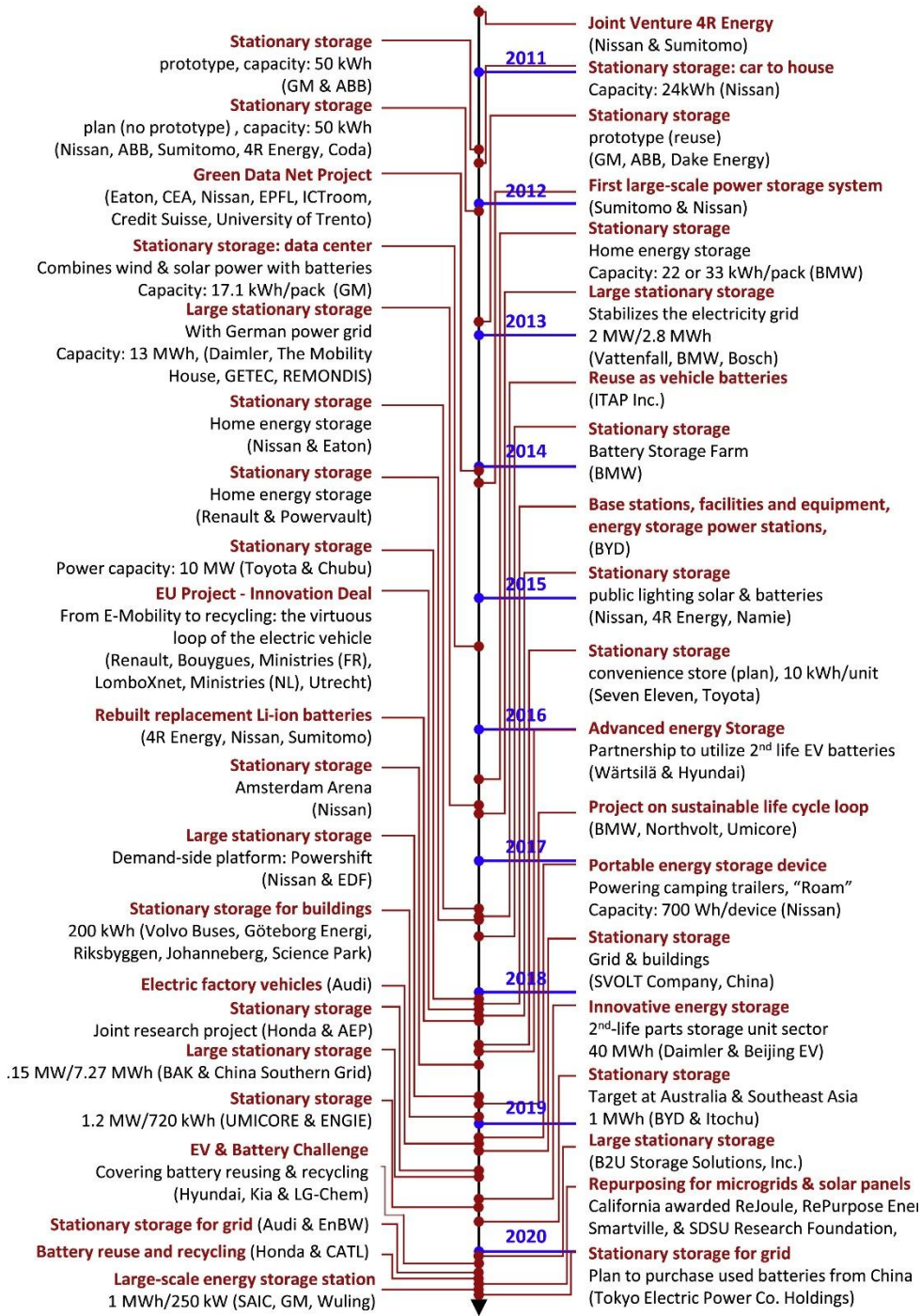


Figure 2.3: A historical overview of industrial projects of second-life battery applications [63]

It is clear that four main trends are evident: (i) the number of projects has increased in the past few years, showing a growing attention to the topic; (ii) several OEMs are participating in second-life application projects; (iii) large-scale stationary Energy Storage System (ESS) applications are the most applied; (iv) the typologies of second-life applications are diversifying.

In this section, the main existing second-life opportunities for batteries are addressed.

2.1.3.1. EV

Reusing in another EV would be the best option in terms of environmental sustainability due to its lower energy and resource intensity required to produce the battery. In this case, the battery would serve its original purpose and remain viable as long as the charge capacity is still high enough. [4] A possible scenario could be a battery coming from a car accident.

The direct reuse is the best alternative from the car manufacturers' perspective, as the product is less manipulated. Additionally, it is the inner cycle of the butterfly diagram (Figure 1.3). However, this point of view raises an important issue related to the battery system's behaviour and the BMS: the battery's performance is entirely dependent on the worst module or cell, and the BMS is not designed for second-life use, with access restricted to the original OEM. Finally, the design and size are not customizable, making the direct reuse not flexible. [64]

A possible solution to the previously described problems is the extraction of modules and cells, followed by the remanufacturing of a new battery. Although this option is very flexible, it may not be financially viable due to the lower battery costs and diminished environmental benefits.

To sum up, this option presents significant challenges, including battery deterioration and reduced performance during its second life. Because of stacking issues, it offers fewer options for adaptability despite having lower costs [28]. Additionally, by lowering the high capital cost of batteries, it helps EV manufacturers obtain a competitive edge over rivals of conventional vehicles [65].

2.1.3.2. BESS

Second-life EV batteries can be utilised in BESS as a support to renewable sources.

Spindlegger et al. [66] applied an LCA (Life Cycle Assessment) approach to compute the environmental performance of repurposed LIBs after their utilisation in EVs, compared to new LIBs manufactured for BESS. They concluded that SLBs show better environmental performance, especially when reusing both the BMS and the module casing. However, some challenges in the feasibility of repurposing strategies are present, such as damage during the disassembly process and the material composition. Additionally, the reuse of the BMS requires a software reconfiguration, feasible accessing the BMS software that contains sensitive data.

The addressed challenges could be softened with the integration of the battery passport, especially in terms of easier disassembly and accessible data.

Moreover, López et al. [67] analysed the potential of the Second Life Battery Energy System (SLBES) integrated in renewable sources, focusing on wind farms. The conducted techno-economic assessment in various scenarios reveals that investments in SLBES are profitable at current market electricity prices, considering future growth

in the EV market. Moreover, from a technical point of view, the installation of a new stationary lithium-ion battery storage system seems similar to SLBES. A similar scenario applies to gas turbine systems, where refurbished batteries can support power and energy generation, providing area frequency and regulation services. This enables the balancing of generation and demand, thereby maintaining the frequency within the working limits [68].

Second-life batteries can be utilised in microgrids, especially in remote or underserved regions, to increase system power supply reliability and improve energy access [60]. Lacap et al. [69] designed, constructed, and operated a commercial-scale microgrid supported by an ESS built with SLBs. This project demonstrated that SBLES, despite having lower SoH, are robust and effective for ESS in microgrids.

2.1.3.3. Industrial Traction Vehicles

This scenario includes forklifts, Automated Guided Vehicles (AGVs), warehouse robots, and other industrial conveyances. The requirements can vary depending on the specific vehicle type and the task to be performed. In this case, it may be crucial that the carbon footprint is below a defined threshold set by companies for their sustainability goals.

2.1.3.4. Light Means of Transport and Low-Speed Vehicle

Light means of transport require lower performance than EVs, making SLBs suitable for this application. Additionally, the battery needed is small, requiring only one or a few modules, which increases feasibility and profitability, as it is possible to refurbish batteries from individual modules.

Ma et al. [70], through a process-based LCA method to evaluate the batteries' lifecycle in different reuse scenarios, identified the reuse in Low-Speed Vehicles as unprofitable due to the lack of renewable energy integration. For this reason, they suggest prioritising ESS applications.

2.1.3.5. Mobile Charging Stations

The mobile charging station is a novel and viable application proposed by Hassini et al. [15]. These stations offer a flexible solution to strengthen existing EV charging infrastructure by being autonomous, movable, and quickly deployable. Powering them with second-life batteries would increase the sustainability of the charging infrastructure.

2.1.3.6. Backup or Emergency Applications

Used batteries can be remanufactured for use in factories and commercial buildings as backup power storage, substituting for diesel generators. [48]

2.1.4. State-of-Health Based Decisions

As addressed in the preceding paragraph, the battery's second-life opportunities are evaluated based on battery performance. The first life determines the conditions of the retired batteries, having a significant impact on the determination of their second-life performance. The increasing number of battery cycles leads to performance degradation in terms of power, energy efficiency, and capacity. [65]

Given the high relevance of the first life in defining the second life performance, a tracking mechanism to track the ageing history of the first life is demanded to distinguish batteries suitable for reuse [65].

Generally, the value considered by several authors as a discerning factor is the SoH, which represents the ratio of current capacity to that of the original battery [65]. It is the most utilised, together with the RUL, because they represent a comprehensive characterisation of battery degradation [63]. Ideally, a new battery has an SoH equal to 100% and it declines over its lifespan due to environmental factors, driving and recharging behaviours, and usage patterns that influence the chemical and physical degradation of battery cells [31].

Unlike other values related to battery performance, the SoH must be computed using one of the several methodologies available in the literature. Consequently, the DBP must contain the parameters employed for the measurement.

Various authors have emphasised that the 70% SoH marked by car manufacturers is not mandatory, and actually, this limit is not expected to be reached due to misuse during the vehicle's lifetime [28]. In order to satisfy a specific use case, batteries must be grouped by similar SoH [71].

The diverse second-life applications can be feasible depending on the remaining SoH, as represented in the Figure 2.4 [71].

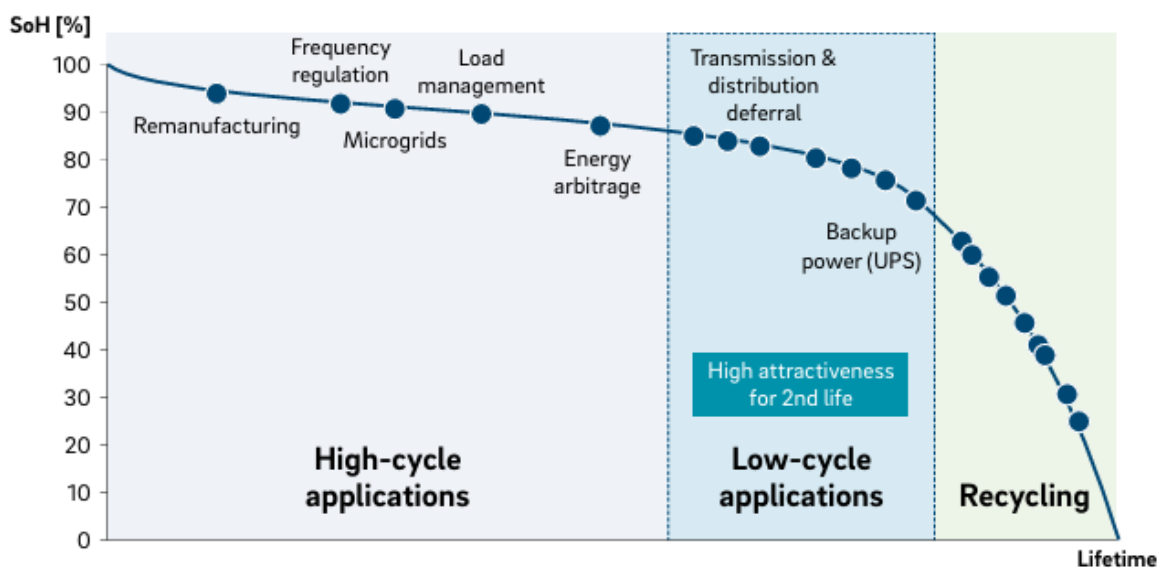


Figure 2.4: examples of use cases for batteries after 1st life [71]

As can be seen, the curve shows a linear downward trend, but after a certain amount of time, the performance—here expressed in terms of SoH—declines precipitously. The term "knee point" or "ageing knee" refers to this change from a linear to a non-linear region, after which the battery's performance, especially its capacity, rapidly declines, and several problems may occur. [65], [72]

It has been shown that the batteries' EOL and knee-point do not match with the majority of chemistries, even though the degradation is faster [65]. On the other hand, it has been studied that LIBs are sufficiently durable to go through both first and second use before reaching the ageing knee, which varies from 45% to 49,5% [73].

This graph is particularly pertinent for cell chemistries such as LFP because it is generally characterised by a longer lifetime and is less commercially attractive for recycling, if compared to other chemistries [71].

Since the majority of used batteries can meet these requirements, repurposing efforts are expected to focus on low-cycle and high-energy applications initially. High SoH batteries are suitable for more demanding applications that require longer cycle lives, such as microgrids. Conversely, those with lower SoH might be better suited for applications with less demand, such as backup power systems. However, relying too much on low-SoH batteries—with their limited adaptability—increases risk because future market dynamics may change how use cases are distributed [71].

Ma et al. [70] set the range at the end of the first life from 70% to 90% of the original SoH, and within 40% and 80% at the end of the reuse phase. Moreover, Canals Casals et al. [74] define the EOL for second-life batteries at 60% SoH, although some applications can extend to 40% SoH. These values are aligned with other studies, confirming the possibility of reusing them until a capacity level equal to 40% [75].

Moreover, in order to ensure a profitable solution, the RUL must be computed as well. It strictly depends on their use; indeed, fast EV charge support applications can last almost 29 years, while self-consumption applications have an RUL of 11 years and area regulation services of about 5 years. [74]

Despite the completeness of the SoH indicator, it does not lack complexities. Indeed, when the battery has already been removed from the vehicle, determining the value requires a manual charge and discharge procedure. [31]

The stored data in the DPP can speed up and automate the prolonged process. Additionally, the BMS is a fundamental tool because it can compute and store the SoH value whenever it is connected to a power source, such as the battery.

According to some studies, the SoH might not be the only way to define the battery's EOL; indeed, based on the performance demands of the driver, once the battery degrades beyond a certain threshold, it may no longer be safe or capable of delivering the required range or power. It should, consequently, be removed from the vehicle. The SoH threshold might cause underuse of the battery. [64]

2.1.5. Value Chain

Porter [76] defined the value chain as the relationship between the company and its suppliers upstream and downstream. This concept has been extended to a global perspective over the years.

The concept “supply chain management (SCM)” is defined as "a set of approaches utilised to efficiently integrate suppliers, manufacturers, warehouses, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimise system-wide costs while satisfying service level requirements." [77]

Traditionally, SCM studies examined the forward movement and transformation of materials from suppliers to the end consumer. However, in the last decades, the reverse flow of products from consumers to upstream businesses has started to get as much attention as the forward flow. Reverse supply chain management (RSCM) is described as the effective and efficient management of the activities required to retrieve a product from a customer and either dispose of it or recover value [78]. Logistics operations, from used goods that the user no longer needs to products that can be sold again, are covered by reverse logistics [79].

The RSC and the forward supply chain together make up the closed-loop value chain [79]. Since a closed-loop strategy promotes long-term sustainability and efficiency, addressing RSC is becoming increasingly crucial for achieving circularity success. Furthermore, the EPR now requires manufacturers in the EU to recover waste batteries [36].

Consequently, when integrating second-life phases, value chain activities differ from traditional and linear value chains. The general supply chain for second-life EV batteries begins with battery collection and ends with recycling. Regarding batteries with satisfactory characteristics, circular economy solutions – including repurposing, refurbishing, distribution, and maintenance – are implemented. Following collection, the batteries undergo testing and sorting in accordance with the SoH evaluation. When using second-life strategies, the battery's installation and, if required, any further maintenance mark the end of the value chain. [48]

The integration of recycling, repurposing, and refurbishment activities that extend battery life is made possible by a circular supply chain. In this way, it lessens the environmental effects of battery manufacturing as well as dependency on the extraction of virgin raw materials. This strategy protects the environment by keeping old EV batteries out of landfills, which lowers pollution levels and increases economic efficiency by decreasing material costs. Therefore, circular supply chains are essential to advancing the sustainability of EOL EVBs while simultaneously reducing waste and conserving resources because they ensure continuous material recovery and reuse. [80]

There is a need for data collection at several levels, including cell, module, pack, vehicle, and external points, to ensure data exchange in the closed-loop value chain [29]. Indeed, an effective circular battery value chain is feasible only if the traceability of EV batteries and the knowledge sharing are guaranteed. Other relevant enablers include designing for a second life, standardising repurposing operations, and advancements in battery hardware and software technology. [48]

In their study, Jussani et al. [81] report a LIB value chain composed of the following phases: component production, cell production, module production, pack assembly, vehicle integration, use, reuse and recycling. Moreover, Rettenmeier et al. [82] describe an EOL EVBs process chain composed of disassembly and recycling, without alternative second-life solutions.

Battery Pass developed a complete battery value chain (Figure 2.5) that highlight the circularity of the process with key circular actions.

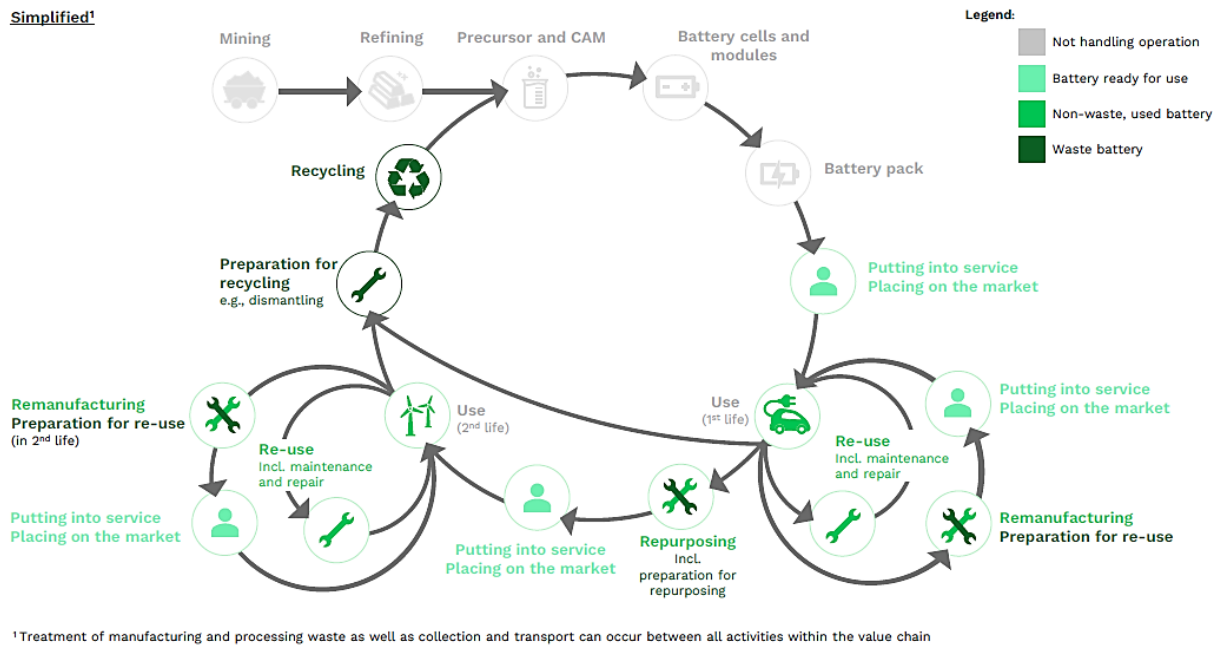


Figure 2.5: Overview on battery handling operations along the value chain [34]

2.1.6. Decision Support System

In contrast to a linear "take-make-dispose" economy, a circular economy requires rethinking production and consumption to slow, close, and narrow resource loops. This necessitates new roles and decision-making contexts for various supply-chain actors [49].

A technoeconomic decision support model for SLBs was created by Zhuang et al. [83] with a particular focus on the crucial choice between recycling and reuse for LIBs from EVs. The three main steps of the suggested roadmap—testing, evaluation, and application—are especially made for OEMs and battery repurposing businesses. The model starts by forecasting resistance growth and capacity degradation at the cell level

using historical data. Then, current distribution, voltage, and module-level capacity are computed to map cell heterogeneity and electrical connections. Finally, simulations are applied to capture the heterogeneity of cells within a module, providing statistical results for the degradation of the module. Additionally, the maximum selling price of SLBs in different applications is determined through an economic analysis using the Net Present Value in comparison to the recycling option.

In contrast to the conventional route, which entails a new battery, EV use, and hydrometallurgical recycling at the EOL, Ma et al. [70] created a prioritised pathway for various battery types and SoH levels. This route contributes to the sustainable growth of the battery industry by incorporating a thorough examination of economic performance and carbon footprint factors. Anyway, the study does not address external benchmarks and requirements in different EOL applications, but it is essential to compare the cost of acquiring and repurposing a used battery—including the cost per charge cycle—with that of newly manufactured batteries tailored for the intended application [71].

2.1.7. Use Cases

Use cases are identified to understand benefits and opportunities in a specific environment.

Consortia – CIRPASS and Battery Pass – identified some use cases concerning batteries and the exploitation of the DPP.

Starting from CIRPASS [30], two main use cases have been identified and described.

Determining an EV battery pack's remaining state of health and rearranging EV battery packs to satisfy the needs of energy storage applications are the two primary goals of the first use case, "Increase volume of EV battery reuse in energy storage applications." The analysis emphasises the advantages and potential enhancements brought about by the DPP, such as lower expenses for technical testing and disassembly and increased worker safety due to a lower risk of incidents.

The second use case defined is "Increase recovery rate of critical raw materials at EV battery end of life," which leads to an increase in material recovery rate, reduction in dismantling, sampling, and treatment costs, and improvement of worker safety.

Moving to the Battery Pass, twelve use cases were identified along the value chain (Figure 2.6) to illustrate the processes that can be enhanced through the adoption of the battery passport, to identify the resulting economic, environmental, and social benefits.

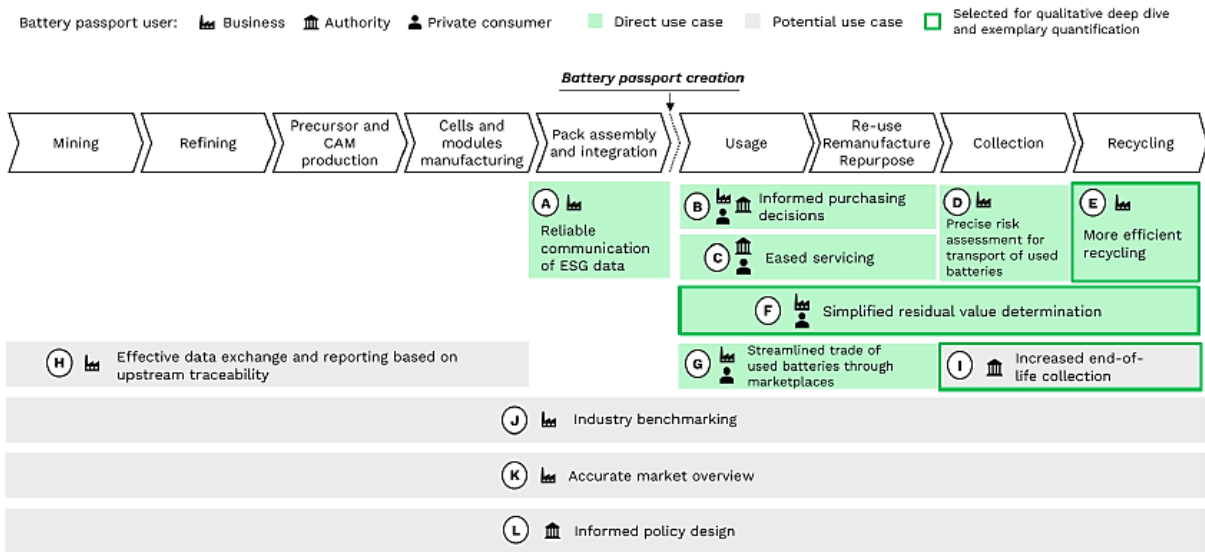


Figure 2.6: Overview of battery passport use cases along the value chain [54]

Jensen et al. [49] identified five use cases, finalised to create specific applications or scenarios where DPPs are utilised by different actors within a circular supply chain. Specifically, the use cases identified are related to the following actors: customer, service provider, manufacturer, supplier, and third-party recycling company. They represent “critical decision points and data needs for actors in a circular supply chain to support product life cycle decision-making”.

Additionally, Berger et al. [56] developed four use cases dedicated to five diverse actors: “value chain development” for the OEM, “the best EV(B)” for the user EV, “support of recycling efforts” for the recycler, and facilitating Sustainable Product Management (SPM) efforts” for the regulatory body. These use cases were created to show how the DPP supports SPM activities and is applicable in the real world. Additionally, they emphasise how various stakeholders can use the DPP's data to improve sustainability and circularity in decision-making scenarios.

2.2. Gaps

Despite the increased focus on circular economy practices and the introduction of the EU Battery Regulation, which requires the use of the Digital Product Passport (DPP), the scholarly literature on these practices is still scattered. While managerial research emphasises supply chain implications, technical studies concentrate on battery diagnostics or recycling processes. Comprehensive standards for traceability and transparency are provided by regulatory frameworks. Existing contributions, however, usually focus on just one dimension. Still lacking, though, is a comprehensive strategy that integrates these elements into a systematic framework.

Despite the increasing importance, the integration of forward and reverse supply chains is not exempt from difficulties and can be represented in various ways.

The literature is rich in works related to the battery value chain; however, there is a lack of comprehensive analysis of the actors in the post-use phase and of the various interactions among them. Indeed, several authors identify the main general phases of battery production, and sometimes also the post-use phase, but without delving into the details of individual actors and their interactions within the whole value chain. Additionally, some studies focus on improving the value chain, but without a strong basis and structure for the value chain itself—for instance, Tajik et al. [84] investigated the role of Digital Transformation (DT) to make more informed strategic decisions and to optimise some phases, in particular, collection, separation, and recycling.

Jussani et al. [81] described a Battery Global Value Chain from the component producer to the reuse and recycling phases, but without exploiting the specific actors and the circular layout; additionally, the second-life actions are gathered in a single phase. The same has been pursued by Nurdiawati and Agrawal [24] who, focusing on the Swedish context, highlighted the possibility of a future circular battery economy through reuse, but without further developing this aspect. Additionally, the need for an effective traceability system to enable closed-loop supply chains [24].

Battery Pass has developed a fairly comprehensive value chain; however, it does not clearly highlight the relationships with key actors and does not delve into the details of some critical phases, particularly remanufacturing. Finally, the CIRPASS consortium identified the main groups of actors and defined their user stories as their interactions with the DPP [85].

Therefore, in the current environment, there is a lack of a comprehensive perspective on battery ecosystems that limits the realisation of battery second-life applications [29]. Reducing environmental damage and increasing equity should be the top priorities in the design of a circular battery economy [43]. Furthermore, a variety of sources of uncertainty, including supply, regulatory, and demand uncertainty, define reverse and, by extension, closed-loop value chains [78]. In the end, material leakage and value loss occur throughout the battery lifecycle due to a lack of current traceability and tracking capabilities. Hence, technology solutions must be proposed [29].

In this regard, the authors thoroughly discuss the lack of information exchange despite the actual presence of the required knowledge; however, they do not propose a concrete solution to reduce this gap. Moreover, Alizadeh Afroozi et al. [75] deeply investigated existing barriers, but without starting from a structured value chain and without offering enablers to overcome them.

Moving to second-life opportunities, the literature defines the importance of reusing batteries in low-performance applications, but without setting a specific standard for decision-making. Additionally, the exploitation of DPP information exchange among different actors can lower the costs related to the manipulation and testing addressed by Kotak et al. [28]. A comparison with the cost of development of new batteries must be carried out to evaluate the benefits of reuse and remanufacturing.

The model provided by Zhuang et al. [83] emerges to be complex in terms of accessibility and not effective as it does not leverage the DPP and the BMS as data sources, despite providing data-driven recommendations on whether to remanufacture or recycle batteries based on their condition, expected second-life degradation, and economic value.

In general, there is no evident adequate standard for an efficient industrial model concerning applied technologies and testing procedures for second-life opportunity deployment.

Additionally, the use cases identified in the literature focus on the single use of the DPP by a limited number of actors, without representing the various interrelations and complexities among the different elements of the system – actors, value chain phases, and the DPP.

While representing the foundation for a concrete and effective use of the DPP, the use cases identified by the Consortia – CIRPASS and Battery Pass – do not highlight the interaction between the actions and stakeholders concerning the specific use cases, limiting the understanding of the implementation process.

Generally, discrepancies between regulatory frameworks and directives, as well as authors' opinions and concerns, highlight an existing gap between theoretical objectives and practical application.

These aspects reveal a clear gap in the literature: no integrated study combines value chain modelling, second-life decision-making support, and structured use cases to demonstrate how DPP data can support technical, economic, and environmental decisions for end-of-life batteries.

2.2.1. Thesis Objective

Based on the mentioned literature gaps, this study addresses the need for the implementation of comprehensive and standardised actions and strategies in managing EOL batteries, exploiting the Digital Product Passport requirements and characteristics. This objective answers the need to improve traceability and to comply with the increased EVB legislation. Indeed, the final objective is to demonstrate how the 2027 implementation of the DPP can enhance and increase second-life opportunities in the battery industry. The goal is to establish a unified framework for identifying second-life applications through secure data exchange among stakeholders across the value chain.

This objective has been pursued and developed over three main sub-objectives:

1. Mapping the closed-loop battery value chain: The need to overcome the existing fragmentation in understanding battery flows, stakeholders, and circular strategies across the lifecycle is the driving force behind the mapping and analysis of the closed-loop value chain. To illustrate where and how second-life

opportunities can arise, this subobjective aims to provide a comprehensive and qualitative picture that combines industrial practices with the regulatory framework.

2. Designing a Decision Support System: The design of a DSS arises from the need 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 applications through use cases: The implementation of use cases answers the need to demonstrate the applicability and usefulness of the DSS in real scenarios. In this way, the concrete help in unlocking second-life opportunities is enhanced.

The reasons and the importance beyond these three sub-objectives are further explained in the following sections.

The study boundaries are related to the EU context, given the increasing attention given to the Circular Economy by the European institutions. Additionally, the DPP regulations and requirements are planned to be first implemented in the EU; for this reason, considering extra-EU regions would have been imprecise and misleading.

2.2.1.1. Mapping the Closed-Loop Battery Value Chain

As noted in previous sections, the importance of a concrete and comprehensive battery value chain has increased in terms of economic significance and environmental and geopolitical implications.

The first sub-objective of this dissertation is to map and analyse a complete closed-loop battery value chain. The complexity of material flows, stakeholder interactions, and information exchange can only be fully comprehended by means of a systematic representation of the entire value chain, even though transparency, sustainability, and circularity are outlined in regulations and industry standards.

This specific objective aims to develop a value chain that serves as a strategic tool to align stakeholders and demonstrate how circular strategies can be integrated into existing procedures.

Thus, the ultimate goal of this objective is twofold: first, to develop a comprehensive representation that helps decision-makers to identify opportunities, risks, and bottlenecks along the chain; and second, to connect this systemic perspective with the actual implementation of the DPP. Therefore, value chain analysis plays a role in connecting regulatory goals with operational procedures and elucidating the roles and interactions of various stakeholders. In this way, the objective contributes to supporting the shift of the battery industry from a linear to a circular model, grounded in well-organised data access, informed decision-making, and a clearer understanding of where and how value can be preserved or regenerated.

2.2.1.2. Designing a Decision Support System

Limited data access, which is required to conduct safety tests and compatibility evaluations for second-life applications, was one of the main obstacles to putting second-life opportunities into practice [4]. Operators in the EPR phase find it challenging to decide whether batteries are appropriate for recycling or remanufacturing due to a lack of information and a high level of market uncertainty [28]. Furthermore, a lot of businesses consider profitability to be the most crucial consideration when making decisions. Despite numerous studies on potential reuse, a validated and structured decision-making process is necessary to determine the optimal use for each component.

Therefore, creating and integrating a decision support system for battery management is a primary objective of this research. This system wants to provide an organised approach to assessing recycling options, residual value, safety concerns, and second-life opportunities. It is designed to serve as a methodological bridge between the need for practical decisions and the availability of information.

The regulatory framework and the DPP guarantee access to standardised data on composition, performance, and sustainability, but they are not enough to guide complex operational choices. This necessitates the use of a systematic framework that can link existing data with practical solutions by methodically assessing recycling options, residual value, safety hazards, and second-life opportunities. The DSS is therefore conceived as a methodological response to this gap.

Ultimately, the purpose of this objective is to demonstrate how the DSS, when combined with the DPP and a comprehensive value chain representation, can provide a structured approach to circular economy decision-making. Such an approach is expected to support compliance with legal requirements, reduce uncertainty, enhance transparency, and open pathways for new business opportunities within the EVB ecosystem.

2.2.1.3. Demonstrating Practical Applications through Use Cases

Creating and executing use cases that illustrate the practical role of the Digital Product Passport and Decision Support System in the battery value chain for the circular economy is another primary objective of the dissertation. Although the regulatory framework establishes challenging standards for sustainability, traceability, and transparency, it takes structured and situation-specific scenarios to convert these standards into actionable practices. According to this perspective, use cases serve as a methodological tool to connect theory and practice by simulating actual operational scenarios in which multiple stakeholders can derive quantifiable benefits from having access to standardised battery data.

Through the analysis of these cases, the thesis seeks to achieve several aims. Its primary goal is to explore the viability and potential effectiveness of incorporating

DPP data into decision-making processes supported by the DSS. Second, it seeks to demonstrate how structured data access can reduce operating costs and uncertainty, while also creating new economic opportunities. Thirdly, it seeks to highlight the potential social and environmental benefits associated with improved resource use, accident prevention, and increased stakeholder trust. Lastly, the use cases are designed to act as representative models, rather than isolated practices, to support regulators, technology providers, and industry stakeholders in implementing data-driven circular strategies for electric mobility batteries.

3 Methodology

This section provides a detailed report of the utilised methodology. In the **Error! Reference source not found.** the flow steps followed in this dissertation are observable.

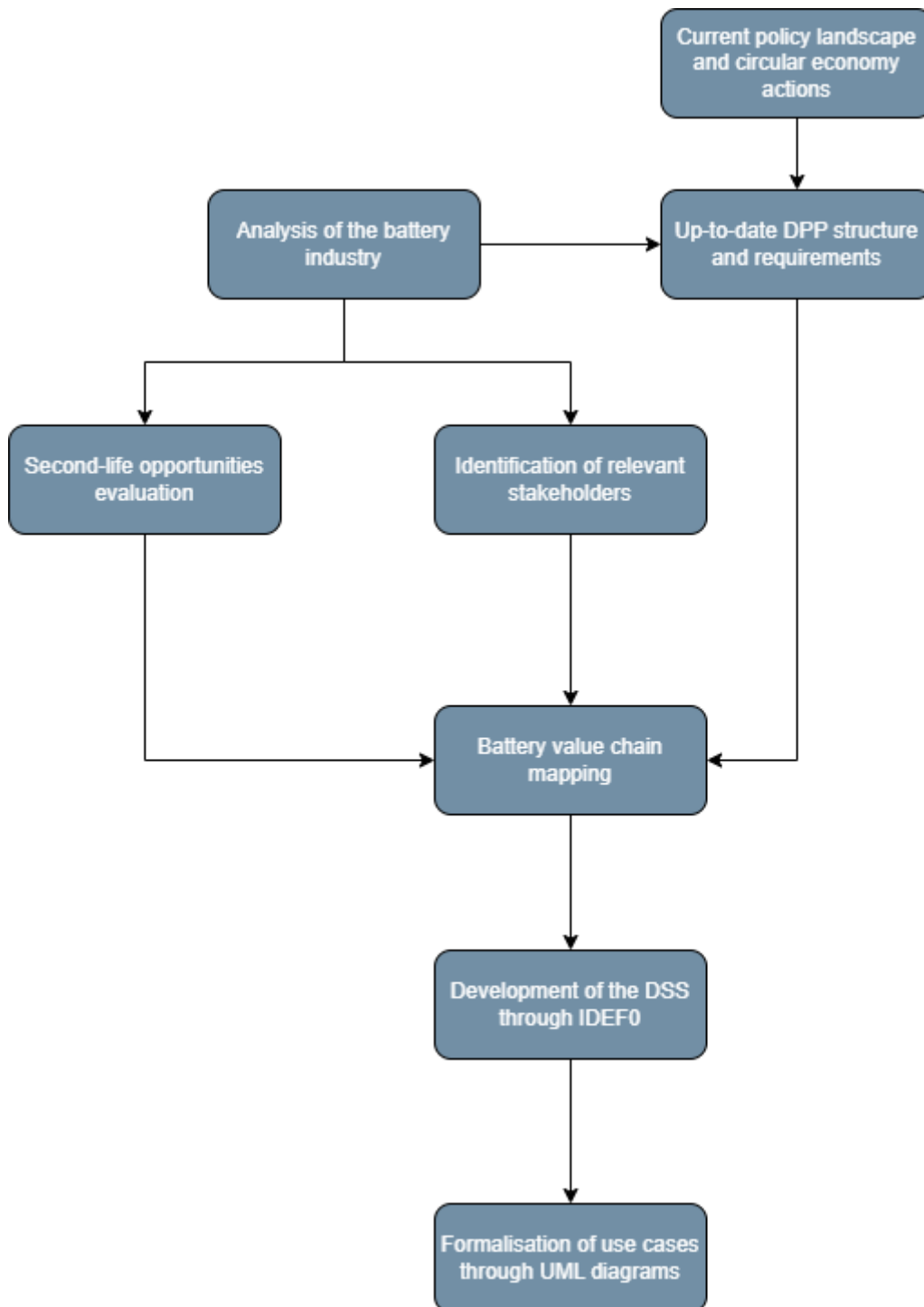


Figure 3.1: Research flow steps

The work is organised as follows: first, a study of the battery industry was conducted to determine its key characteristics, relevant stakeholders, and existing second-life opportunities, both in the current and future landscapes. In parallel, current regulations and circular economy actions were examined to establish a connection with the requirements and framework of the Battery Passport.

By merging these two aspects, a detailed mapping of the battery value chain was developed, highlighting the business relationships, material flows, and information flows, with a specific focus on DPP data attributes.

To address the challenge of selecting the most suitable second-life opportunity, considering both the battery's features and market needs, a Decision Support System was developed, built upon previous funding. Based on this system, several use cases were formalised along the value chain to visually and theoretically explore practical applications.

In the following paragraphs, the approaches and tools utilised to develop the value chain, the DSS, and the related use cases are described.

3.1. Mapping and Analysis of the Value Chain

The value chain mapping methodology used in this thesis follows the guidelines and directions of MacCarthy et al. [86]. The authors state that value chain mapping is a crucial first step in effective strategic supply chain management. This methodology begins by defining the purpose and boundaries of the value chain in question, followed by identifying the main phases.

The proposed mapping highlights the significance of graphical representation to provide a clear view of the network of actors involved. This includes the main economic entities (nodes), the connections between them (links), and the flows that characterise them. These flows can consist of materials, information, and financing, which may move in various directions along the chain.

Through a formal hierarchy shown in Figure 3.2, the authors also propose an organised classification of value chain maps. This hierarchy comprises global value chain maps (GVC), supply networks, specific supply chains (supply chains), value stream mapping (VSM), and process mapping.

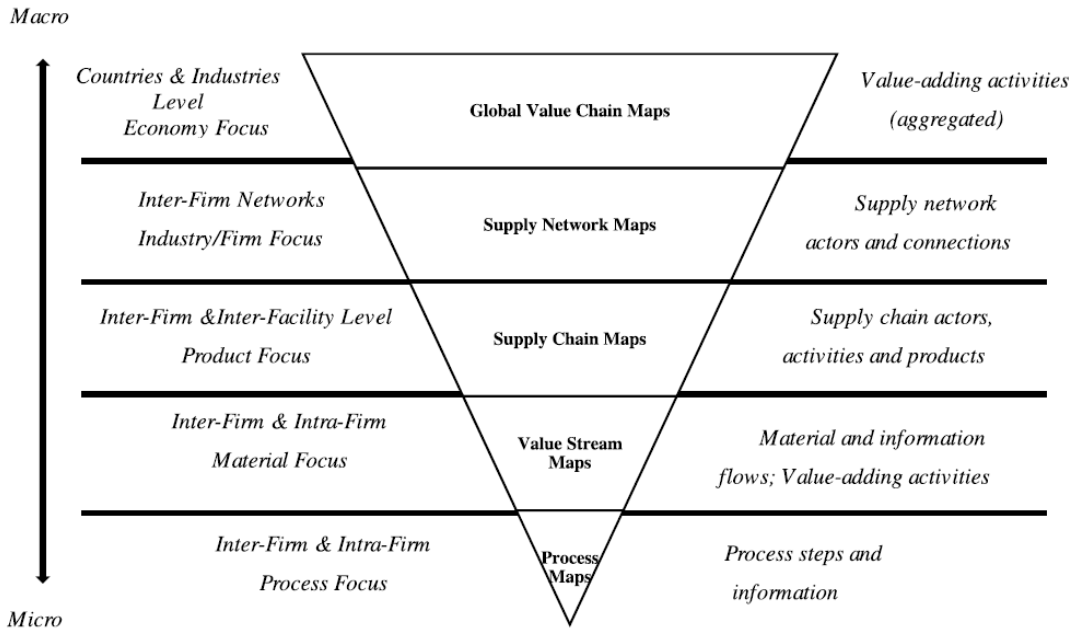


Figure 3.2: Hierarchy for supply systems mapping [86]

It makes it possible to determine with clarity which unit of analysis is best for the study, guaranteeing consistency and promoting stakeholder communication.

The proposed method utilises both primary sources, such as direct interviews, field observations, and company documentation, as well as secondary sources, including commercial and public databases, to gather accurate information. Finally, the importance of using advanced software tools for visualising and analysing the value chain is emphasised. These tools improve the ability to identify risks, inefficiencies, and opportunities for strategic improvement.

The value chain mapping was conducted using a qualitative approach, drawing on multiple data sources. The first step involved defining the boundaries; then, the methodology included an industry analysis aimed at identifying the leading actors, flows, and challenges in the battery sector. This was complemented with academic literature, regulatory documents, and insights from institutional and industrial reports, which provided a comprehensive overview of the current practices and emerging trends. The consecutive phases of an EV battery journey, and the correspondence with the battery actors identified by the Battery Pass Consortium [34] have been considered.

This phase generated two main outputs. First, identify the stakeholders involved across the different life-cycle phases, along with their respective roles and interactions. Second, the recognition of R-strategies (such as reuse, remanufacturing, and recycling), which represent the core circular economy options applicable at different stages of the battery value chain.

From these results, the final output of this process was developed: the value chain mapping, which visually represents stakeholders, interactions, regulatory drivers, and circular economy strategies in a structured manner.

Ultimately, the result was discussed through a peer review, where the value chain was compared to a recent and updated article mapping the value chain, written by Wellten et al. [29].

As mentioned, the data sources used to identify the actors involved in the battery context are numerous. Firstly, the industry analysis led to the identification of the main stakeholders operating in the market. Additionally, the documents proposed by the Consortia were integrated, with a particular focus on the battery actors reported in the Chapter 2.1.2.3. Finally, the literature sources discussed in the Chapter 2.1.5 were considered.

The whole analysis and mapping were integrated with the regulatory framework, especially the EU Battery Regulation and the Ecodesign for Sustainable Products Regulation. This ensured that the mapping reflected not only the industrial and technological perspective but also the compliance requirements and obligations for each actor along the chain.

The developed value chain is characterised by a closed loop, where boxes represent the actors and the arrows represent the material exchanged (physical flow). Particularly, there are input and output arrows. Additionally, a table is provided to describe the information flow passing through the actors.

Since the sources employed (industry analysis, literature, reports, and regulations) are primarily descriptive and conceptual, the mapping is the result of a qualitative methodology. This allows for a holistic and systemic representation of the value chain.

3.2. Design of a Decision Support System

The Decision Support System (DSS) was designed using the IDEF0 methodology, a structured modelling tool that represents processes through functions, inputs, controls, outputs, and mechanisms, as further detailed in this section. This approach was selected because it allows for a clear and hierarchical representation of the decision-making framework, highlighting dependencies and flows between elements.

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 process begins by clearly defining the purpose, boundaries, and viewpoint of the system under consideration. Then, it proceeds with a hierarchical decomposition of the main activities (parent diagrams) into more detailed sub-processes (child diagrams). Diagrams visualise each function, illustrating the decision-

making process and allowing a recursive breakdown until the required descriptive granularity is achieved.

Another crucial element in this stage is the regulatory framework. In fact, it is specifically included as a control element in the DSS model. Regulations that govern the admissibility of strategies, establish performance standards, and impact the distribution of responsibilities among actors, such as the EU Battery Regulation and the Ecodesign for Sustainable Products Regulation, act as both drivers and constraints in the system.

Furthermore, the DSS is designed to be integrated with the DPP, which provides dynamic and standardised data on battery characteristics, performance, and usage history, serving as inputs to the decision logic.

The usefulness of the DSS is further demonstrated through the development of specific use cases, whose methodology is described in the following section. In addition to showing how the DSS can be used in practice to support second-life decisions, these use cases also serve as a demonstration mechanism that permits iterative modifications to the DSS structure. The system was gradually improved in this manner, guaranteeing alignment between the theoretical model and its actual application.

The following explanation of the tool utilised is functional in understanding how this framework has been represented.

The IDEF (Integration Definition for Process Modelling) methodology is a recognised and structured method for the functional modelling of complex systems, based on SADT™ (Structured Analysis and Design Technique™), developed by Douglas T. Ross and SofTech, Inc. [87]. It serves as an engineering tool to support the functioning and management of needs assessment, benefits evaluation, requirements definition, functional analysis, systems design, maintenance, and the establishment of baselines for continuous improvement. It defines a graphical modelling language with specific syntax and semantics, along with a comprehensive methodology for developing models.

It provides a visual and organised approach to creating models, representing system functions and their relationships, supporting the design of decisions, actions, and activities. The goal is to enable experts to understand problems from different perspectives and levels of abstraction [88].

In particular, IDEF0 is dedicated to function modelling, while other IDEF methods are devoted to information, or data modelling, simulations, process, object-oriented projecting, and others [88].

Each function (represented on a diagram by a box) is enriched by the identification of the data and objects inter-relating those functions (represented by arrows): inputs, outputs, controls, mechanisms (resources), and calls, as represented in the Figure 3.3.

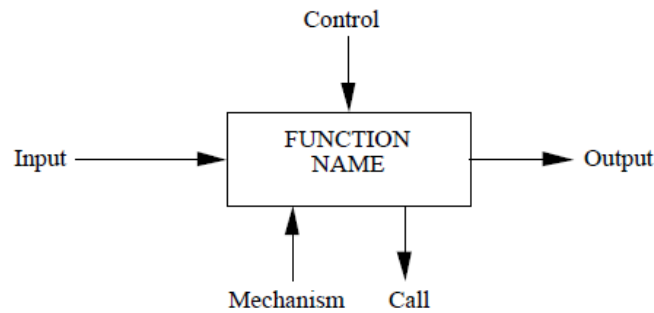


Figure 3.3: Function Box and Data/Objects Arrows [87]

Functions can be utilised to represent several elements: activities, actions, processes and operations [89]. In this thesis, they represent activities executed by the value chain actors.

IDEF0 diagrams make it easier to understand how components interact by mapping the information flow and decision logic across functions. This methodical approach enhances system comprehension and transparency by identifying and analysing important information flows. Additionally, it facilitates good communication between stakeholders, guaranteeing methodological alignment. This aspect is a crucial component of the system's proper and effective implementation. Additionally, a node tree (high-level context diagram) allows for catching the complete decomposition in a single diagram.

Ultimately, the IDEF0 methodology facilitates the definition of interactions across various systems and subsystems, enabling regular updates of critical data for the optimal and sustainable management of resources and processes.

It can be utilised in several business process improvement strategies and methodologies. For this reason and due to its flexibility and clarity, it is widely implemented in the research community [89].

In this thesis, the adoption of IDEF0 ensured a structured representation of the DSS, making explicit the connections between stakeholders, regulatory drivers, and DPP-enabled data flows. This provides the foundation for the subsequent use cases, where the system is applied to practical scenarios.

3.3. Development of Use Cases

Use cases were developed to bridge the gap between the conceptual Decision Support System and its practical application along the battery value chain.

The graphic representation of the use cases was pursued through the UML methodology. The Unified Modelling Language (UML) methodology is an international standard for modelling and documenting complex software systems. It

provides a set of graphical and textual tools that help visualise, specify, construct, and report the elements of a software system and their interactions. [90]

UML use cases are vital tools for representing the system's functionality from the perspective of the involved actors. It is a coherent unit of functionality expressed as a transaction among actors and the system. This viewpoint supports a clear understanding of user needs and system behaviour. [90]

Each use case is examined through detailed descriptive scenarios that define the expected behaviour of the system in various operational situations, clarifying both functional and non-functional requirements.

Additionally, UML facilitates relationship modelling through the use of inclusion and extension mechanisms. Inclusions identify actions that are dependent on other actions, whereas extensions define actions that are extensions or more intricate variations of earlier actions. [90]

All things considered, the use of UML methodology for representation promotes transparent communication between all parties involved, leading to better design and development. This increases the likelihood of successful implementation by assisting in the creation of robust, scalable, and integrated systems.

The methodology adopted for the use cases exploits the UML tool. The primary steps of the applied method are the following:

1. Selection of representative scenarios: The results of the value chain mapping and the DSS structure were used to identify particular phases and difficulties along the battery value chain. These scenarios align with crucial decision-making moments where combining DPP-enabled data with regulatory requirements could improve circular strategies.
2. Actors and interactions definition: The pertinent stakeholders were mapped for each scenario, along with their roles, duties, and information requirements. Users, external systems, and other software elements are examples of these actors. Among the actors, the DPP plays a crucial role in providing the necessary data and interacting with the system and the other users.
The use cases were guaranteed to be in line with the regulatory framework thanks to this step. It ensured a thorough understanding of the operational context of the system, while reflecting the multi-actor nature of the battery ecosystem.
3. UML modelling: UML diagrams were used to illustrate the interactions between actors and the system for each use case. The diagrams formalised how industrial practices, regulatory restrictions, and DPP data come together to

support second-life decisions. Diagrams show the necessary information flows, the system functionalities involved, and the actions taken by the actors. It is simpler to understand the relationships between actors and system functionalities thanks to this visualisation.

4. Application of the Battery Pass framework: To ensure consistency with current European initiatives, the Battery Pass framework guided the design of the use cases. Particularly, for each use case, the applicability along the value chain, the situation without and with the Battery Passport, mandatory and voluntary data, and the benefits – economic, environmental, and social - derived by the use case application are defined. [54]
5. Iterative refinement of the DSS: The use cases were not conceived as static illustrations, but as demonstration mechanisms. Each case contributed to showing the applicability of the DSS structure by testing its assumptions and illustrating its practical value in different contexts.

Additionally, this process to choose and describe the use cases is aligned with the one utilised by CIRPASS [30], but focusing on batteries only. The Consortium pursues the following steps:

1. Considering the battery's characteristics and DPP data composition
2. Identification of actions implemented in the value chain previously developed
3. Identification of stakeholders involved in those actions
4. Description of specific use cases

This methodology, which integrates a standardised language with two consortium methods, ensures a comprehensive and detailed individualisation and description of the use cases.

4 Results

This section delves into the main findings of the sub-objectives described in the Chapter 2.2.1.

4.1. Battery Value Chain Mapping and Analysis

As addressed by Wellten et al. [29], the information sharing through Battery Passports encounters two obstacles. Firstly, managing second-life strategies involves an ecosystem with many diverse actors that lack the homogeneity of linear value chains. Secondly, usage directly impacts the value of EV batteries, making the equitable sharing of such information problematic. Additionally, further supply chain issues are related to the battery materials, including the geographical distribution of suppliers, resource limitations of specific battery materials, associated sustainability risks, and volatile prices of raw materials.

The mapping has been done considering the distinct phases of the EV battery journey, from the manufacturing stages through second-life and final recycling.

The mapping began with the definition of boundaries, considering a cradle-to-cradle approach: the value chain was examined from resource extraction (cradle) to the use phase and the reintroduction of materials into the cycle (cradle). This choice is because circularity requires cradle-to-cradle life cycle management [6].

4.1.1. Value Chain

Figure 4.1 depicts the comprehensive value chain, which comprises an extensive network of stakeholders involved in the manufacturing and post-use processes, as well as intricate business, information, and material flows among them. Numerous actors are involved, each with distinct yet related roles. Determining where value is created and spotting opportunities or critical points for circularity requires an understanding of these roles and interdependencies.

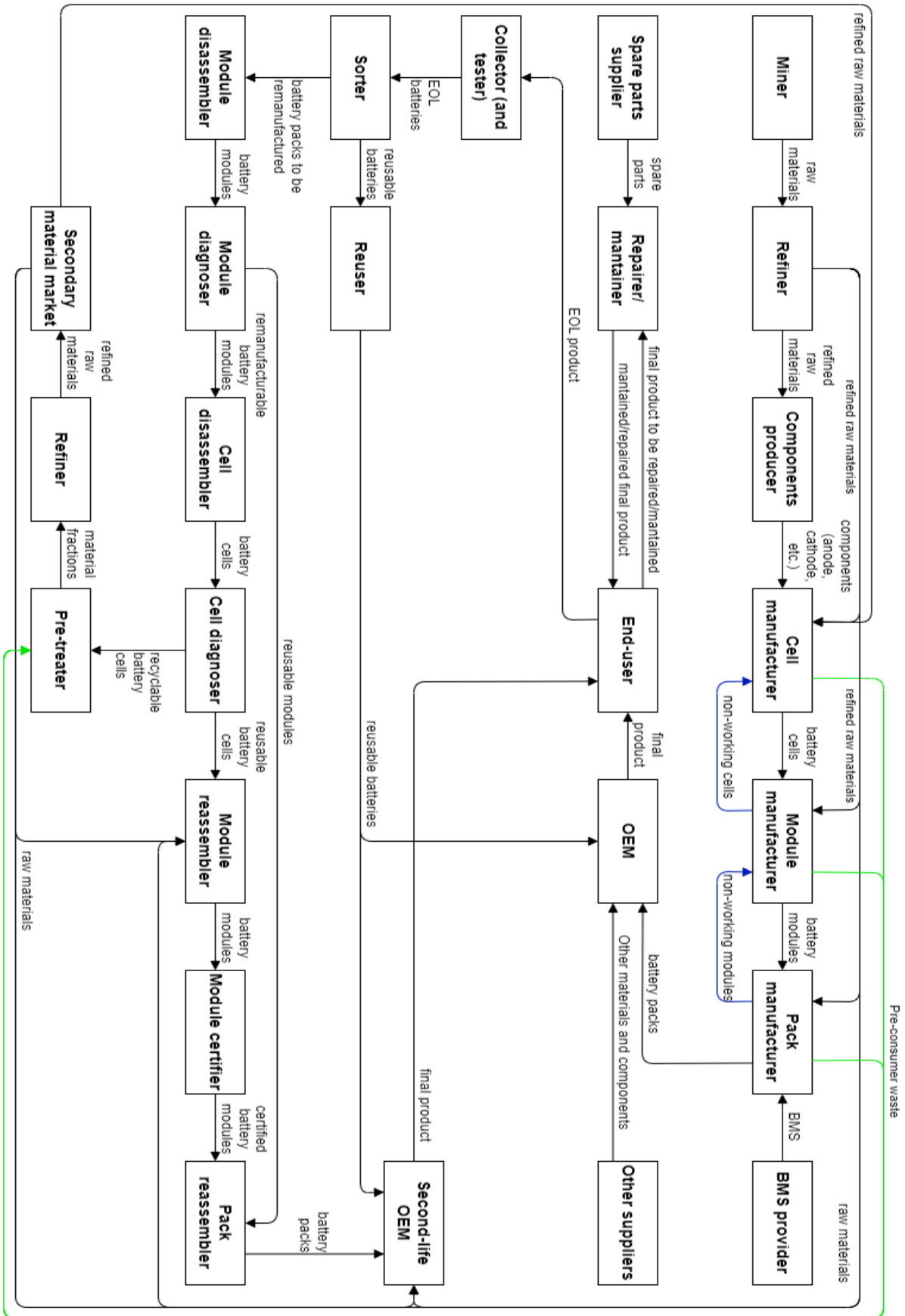


Figure 4.1: Battery Value Chain

The first part is quite linear, but, unlike the traditional linear supply chain, the actors can exchange materials with the secondary material market to obtain new materials for production. At the same time, they can send the scrap and pre-consumer waste to the pre-treater to produce new raw materials.

Additionally, for example, the module manufacturer can send a faulty cell back to the cell manufacturer for direct repair if it is defective. These extra steps can improve waste management and make the production process more sustainable.

The first step in the value chain is the extraction and refinement of the raw materials needed for the production of batteries, such as lithium, cobalt, nickel, graphite, and manganese (Figure 4.2). Miners and refiners are the main participants in this stage, and they are in charge of ensuring the quantity, quality, and purity of the materials. Traceability and due diligence requirements are now essential, though, to confirm adherence to European laws regarding the ethical sourcing of raw materials. Data about the materials' origin, effects on the environment, and chemical and safety properties are thus included in the information flow.

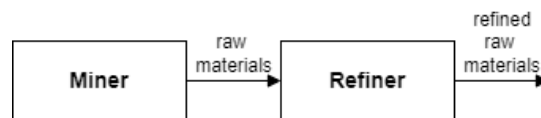


Figure 4.2: Value Chain: Extraction and Refinement

Once refined, the materials are transformed into active components (cathodes, anodes, electrolytes) by component manufacturers, who in turn supply cell manufacturers. Cell manufacturers assemble materials into cells of various geometries and chemical compositions, which are then integrated into modules by module manufacturers and finally into battery packs by pack manufacturers, who incorporate the BMS supplied by a BMS supplier. These stages (Figure 4.3) generate the main value-added flows, as combining materials into a functional electrochemical product requires advanced technological know-how, high safety standards, and significant production investments. In terms of information, data relating to performance (capacity, internal resistance, efficiency, etc.), environmental parameters (carbon footprint of production, and others), and assembly and disassembly instructions are recorded, which will be essential for the subsequent stages.

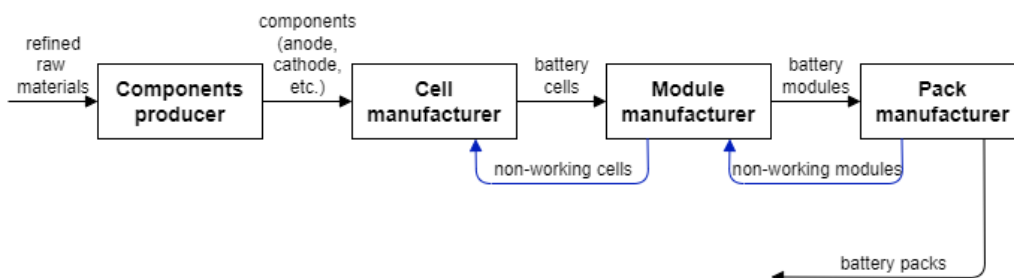


Figure 4.3: Value Chain: Battery Pack Manufacturing

In these phases, the scrap generated during production (green arrows) is sent to the recycling process to prevent the loss of valuable materials. Additionally, to further reduce the environmental impact and resource waste, non-working elements (blue arrows) are sent back to the corresponding manufacturer for repair.

The battery packs are then supplied to automotive OEMs, who integrate them into electric vehicles and bring them to market. At this point, the DPP is created by the OEM, incorporating all the information coming from previous actors.

At the end of their primary life in the vehicle (Figure 4.4), batteries enter the post-use phase, which involves actors such as reusers, collectors, testing centres, and repairers. In this phase, the actual condition of the battery is determined through electrical and chemical tests, and a decision is made as to whether it is suitable for direct reuse, remanufacturing, or recycling.

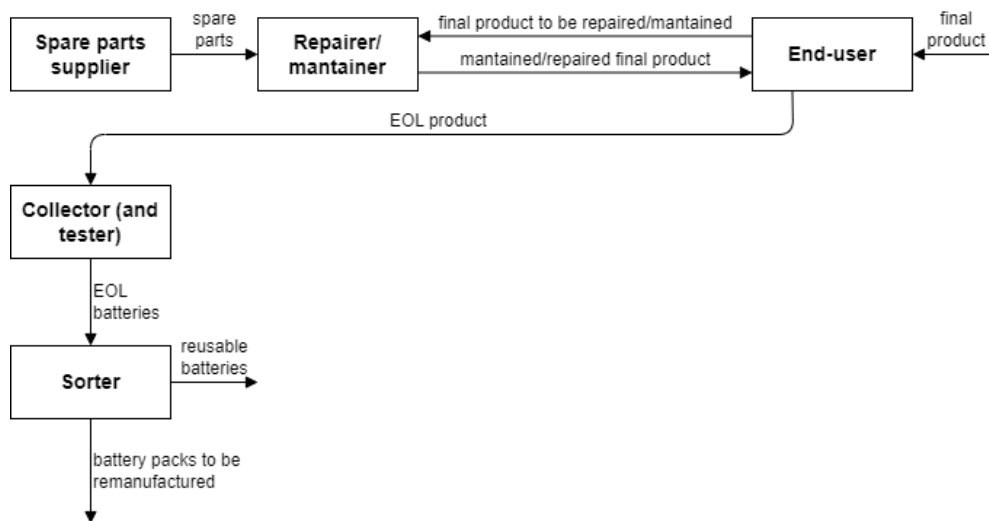


Figure 4.4: Value Chain: End of First Life

The value chain is designed in alignment with the principles of the Butterfly diagram, prioritising the inner cycles whenever possible. Indeed, throughout the product lifecycle, batteries must be maintained and repaired as needed to ensure maximum lifespan. For this purpose, a direct relationship between the repairer and spare parts providers is considered.

Once the battery reaches the first end-of-life, it is collected and tested by the collector to assess its status and physical and chemical conditions.

The batteries are sent to the sorter, who separates the products between reusable and non-reusable based on the collector's test reports. In the first case (Figure 4.5), the batteries are passed through the reuser, who reintroduces them into the market. Particularly, they can be introduced in the original market with the same function or in a secondary market, based on the battery's characteristics and market requirements.

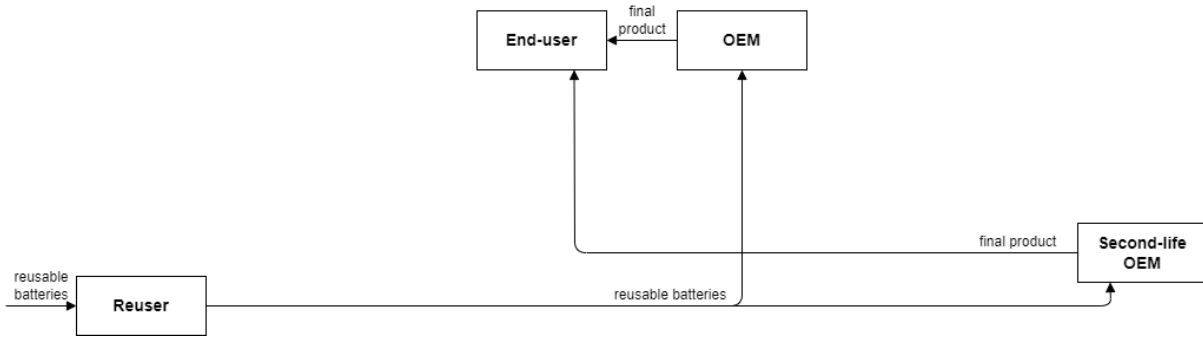


Figure 4.5: Value Chain: Reuse

The remanufacturing process (Figure 4.6) starts with the disassembly, which begins with the pack and module disassembly, followed by module diagnosis. At this stage, the modules are tested and evaluated. Modules considered suitable for remanufacturing are directly sent to the module certifier, while unsuitable modules are disassembled into individual cells. The disassembling in cells should be performed because the pack's cells suffer from the cell-to-cell variation effect, especially in series-connected batteries. Indeed, different operating conditions and load profiles cause individual life cycles to be possibly diverse from cell to cell [91].

Direct module recycling is avoided since it represents the furthest loop of the Butterfly Diagram. Moreover, even in low-performing modules, some cells could manifest a SoH above the average.

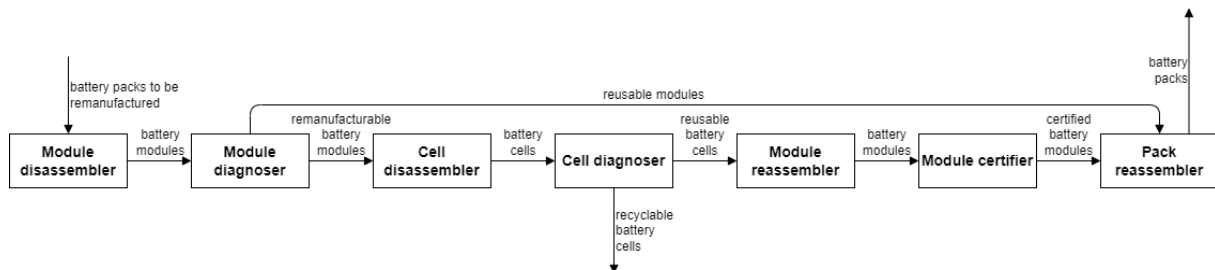


Figure 4.6: Value Chain: Remanufacturing

The cells are diagnosed, and if they meet the requirements, are reassembled into modules. Once reassembled, the modules are certified, assembled into packs, and supplied to second-life OEMs. On the other hand, unsatisfiable cells are recycled. Particularly, they go through the pre-treater where they are discharged and prepared, and then shredded. The materials are separated and sent to the refiner, who recovers them, meeting the grade standards required by the industry. At this point, the materials can be sold in the secondary material market. The customers of this market can be located along the value chain itself, such as CAM producers or module reassemblers, fuelling a virtuous cycle of a circular economy and reducing dependence on virgin raw materials.

In the post-use phase, various information is exchanged among actors to make action feasible and effective.

The role of the remanufacturer could, and should, be performed by the manufacturer itself to exploit knowledge. Indeed, it would know how the battery has been assembled, avoiding the need for reverse engineering and accelerating the process. The DPP will contain the manual for disassembly; anyway, previous knowledge about the product eases and improves the operations. Additionally, many synergies can be utilised, like existing plants, reverse logistics, and the value network.

As mentioned, all actors included in the value chain require information to complete their actions and activities from both a material and business perspective. At the same time, they can and must provide data about the transformations they have made at their level.

The DPP is a valuable means of disseminating knowledge and information among all stakeholders of the value chain. Indeed, the stakeholders' roles and interactions with it are relevant to implementing and exploiting the DPP in all possible ways.

Data must be at different granularity levels according to the input-output transformation of the single step: materials, components, cells, modules, and packs. For instance, the module manufacturer needs information about cells at the cell granularity level and must provide knowledge about the modules produced at the module granularity level. All this information is fundamental to translating the battery's modularity into the DBP, which should have a modular data representation and accessibility.

The detailed identification of the information flow in the input and output of each phase of the value chain has been carried out by analysing the DBP attribute requirements and considering actors' needs and ability in providing such information [58].

The exhaustive information flow is accessible in the Table 1.

Table 1: Value chain information data

Actor	Input	Output
Miner	<ul style="list-style-type: none"> • Compliance and safety standards 	<ul style="list-style-type: none"> • Critical raw materials • Hazardous substances (name, classes, and/or categories) • Substances of very high concern • Extraction place • Raw material extraction carbon footprint • Provenance information

		<ul style="list-style-type: none"> • Impact of substances on the environment, human health, and safety
Refiner	<ul style="list-style-type: none"> • Compliance and safety standards • Quality and purity levels required • Critical raw materials (from the miner) • Feedback on materials recyclability (from the recycler) 	<ul style="list-style-type: none"> • Critical raw materials • Refinement carbon footprint • Impact of substances on the environment, human health, and safety • Provenance information
Component producer	<ul style="list-style-type: none"> • Demand forecast • Critical raw materials (from miner and refiner) • Information about substances (from miner and refiner) • Required chemistry • Product performance and testing standards required • Feedback on materials recyclability (from the recycler) 	<ul style="list-style-type: none"> • Manufacturer ID, date, and place • Critical raw materials • Battery chemistry • Name of the cathode, anode, and electrolyte materials • Composition of the cathode, anode, electrolyte materials, and recycled content share (to ease the calculation of recycled content, recycling efficiencies, and EOL value) • Bill of materials • Location and concentration range of hazardous substances • Components production carbon footprint • Cadmium and lead symbols • Pre and post-consumer recycled material share
Cell manufacturer	<ul style="list-style-type: none"> • Demand forecast • Required geometry • Required chemistry 	<ul style="list-style-type: none"> • Critical raw materials • Manufacturer ID, date, and place • Recycled content share

	<ul style="list-style-type: none"> • Location and concentration range of hazardous substances (from the components producer) • Cadmium and lead concentration (from the component producer) • Feedback from the cell diagnoser • Feedback on materials recyclability (from the recycler) 	<ul style="list-style-type: none"> • Pre and post-consumer recycled material share • Location and concentration range of hazardous substances • Cell manufacturing carbon footprint • Cell weight • Cadmium and lead concentration • Initial internal resistance on the battery cell level
Module assembler	<ul style="list-style-type: none"> • Demand forecast • Module performance and safety requirements and specifications • Required design and specifications • Location and concentration range of hazardous substances (from precedent actors) • Cadmium and lead concentration (from the cell manufacturer) • Feedback from the module diagnoser • Feedback on materials recyclability (from the recycler) • Feedback from the cell disassembler and module diagnoser 	<ul style="list-style-type: none"> • Manufacturer ID, date, and place • Critical raw materials • Recycled content share • Pre and post-consumer recycled material share • Location and concentration range of hazardous substances • Module manufacturing carbon footprint • Postal, e-mail, and web addresses of sources for spare parts • Module weight • Initial internal resistance on the battery module level • Number of cells used and layout • Wiring diagram • Manual for the disassembly of the battery module
Pack assembler	<ul style="list-style-type: none"> • Demand forecast excluding reusable batteries 	<ul style="list-style-type: none"> • Manufacturer ID, date, and place • Battery category • Battery weight • Battery status (original)

	<ul style="list-style-type: none"> • Required pack design and specifications • Location and concentration range of hazardous substances (from the cell manufacturer) • Cadmium and lead concentration (from cell manufacturer) • Cells and modules characteristics • Feedback on materials recyclability (from the recycler) • Feedback from the module disassembler 	<ul style="list-style-type: none"> • Location and concentration range of hazardous substances • Pack manufacturing and battery carbon footprint • Critical raw materials • Recycled content share • Pre and post-consumer recycled material share • Manual for disassembly and dismantling of the battery pack • Postal, e-mail, and web addresses of sources for spare parts • Meaning of labels and symbols • Safety measures, instructions, and extinguishing agent • Rated capacity • Nominal, maximum, and minimum voltage • Original power capability • Maximum permitted battery power • Cadmium and lead concentration • Ratio between nominal allowed battery power and battery energy • Initial round-trip energy efficiency • Initial internal resistance on battery pack level • Expected lifetime: Number of charge-discharge cycles (individual battery) • Temperature range • Exploded view diagram
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OEM (REO)	<ul style="list-style-type: none"> • Demand forecast • All the information reported by previous actors is to be included in the DPP by the OEM as the REO • Regulations and specifications 	<ul style="list-style-type: none"> • Information reported by manufacturers to be included • Battery Passport Identification and REO Identification • EU declaration of conformity (and corresponding ID) • Information on the due diligence report • Battery carbon footprint, carbon footprint performance class, carbon footprint maximum threshold • Separate collection labels • Cadmium and lead symbols • Manual for the removal of the battery from the appliance • Role of end-users in contributing to waste prevention • Role of end-users in contributing to the separate collection of waste batteries • Information on separate collection, take back, collection points, preparing for reuse or repurposing, and recycling operations • Cycle-life reference test • Capacity threshold for exhaustion • State Of Certified Energy (SOCE) threshold for exhaustion
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		<ul style="list-style-type: none"> • Warranty period of the battery • Meaning of labels and symbols • Dynamic data about SoH (Current internal resistance and internal resistance increase on battery pack level. individual battery: SoC, capacity, round-trip energy efficiency and capability fade; remaining usable battery energy, capacity, and power capability (not mandatory); number of charge-discharge cycles, time spent in temperature outside the range; number of deep discharge events; recording of accidents) updating through the BMS • Third-party assurances and recognised schemes; supply chain indices • Repair points addresses
End-user	<ul style="list-style-type: none"> • Performance and durability data (e.g., SoH to adopt better habits to enhance battery health and longevity) • Warranty period of the battery • Repair points addresses • Tips to extend the battery life • Role of end-users in contributing to waste prevention 	<ul style="list-style-type: none"> • Feedbacks • Performance data (through incentives): environmental factors that might affect the battery's life (temperature, humidity)

	<ul style="list-style-type: none"> • Role of end-users in contributing to the separate collection of waste batteries • Information on separate collection, take back, collection points, preparing for re-use, preparing for repurposing, and recycling operations • Meaning of labels and symbols • Impact of substances on the environment, human health, and safety • Separate collection label (WEEE label) • Cadmium and lead symbols • % of carbon footprint consumed 	
Repairer	<ul style="list-style-type: none"> • Safety measures/instructions • Original status and values (capacity, state of charge, power capability, energy) • Spare parts addresses 	<ul style="list-style-type: none"> • Occurred maintenance • Static data updating in case of significant changes to the battery
Collector (and tester)	<ul style="list-style-type: none"> • Manual for the removal of the battery from the appliance • Battery specifications to determine handling requirements • Safety measures/instructions • Information on separate collection, take back, collection points, and preparing for re-use, preparing for 	<ul style="list-style-type: none"> • Issues or accidents during the collection phase • Results of test reports • Battery carbon footprint • Battery status • SoH • SOCE • Certified usable battery energy • Remaining usable battery energy • Remaining capacity

	<p>repurposing, and recycling operations</p> <ul style="list-style-type: none"> • Battery status • Battery category • Battery chemistry • Capacity and SOCE threshold for exhaustion (to decide if the battery can be reused) • Original status and values (capacity, state of charge, power capability, energy) to benchmark • Battery State Of Health 	<ul style="list-style-type: none"> • Remaining power capability • Capacity fade • Power capability fade • SoC • Round-trip energy efficiency fade • Number of (full) charge-discharge cycles
Sorter	<ul style="list-style-type: none"> • Battery's SoH (from tester and OEM) • Tester's results (physical and chemical conditions) • Specifications (chemistry) and requirements • Safety measures and instructions • Hazardous materials information • Information on separate collection, take back, collection points, and preparing for re-use, preparing for repurposing, and recycling operations 	<ul style="list-style-type: none"> • Battery status • Safety handling • Transportation requirements • EOL recommendations • Estimated material recovery • Percentage of batteries to be reused • Percentage of batteries to be remanufactured
Reuser	<ul style="list-style-type: none"> • Results of test reports • Capacity and SOCE threshold for exhaustion (to decide if the battery can be reused and how) • Battery-tested SoH • Spare parts addresses 	<ul style="list-style-type: none"> • Data updating • Battery status (reused) • Battery category • SOCE • Certified usable battery energy • Remaining usable battery energy • Remaining capacity • Capacity fade

Recycler	<ul style="list-style-type: none"> • Separate collection label (WEEE label) • Manual for the disassembly and dismantling of the battery pack • Safety measures/instructions • Quality requirements • Hazardous substances (name, classes, and/or categories and substances of very high concern) • Composition of the cathode, anode, electrolyte materials, and recycled content shares • Information on separate collection, take back, collection points, and preparing for re-use, preparing for repurposing, and recycling operations 	<ul style="list-style-type: none"> • Battery status (recycled) • Recycling carbon footprint • Quality specifications satisfaction • Recycling efficiency • Material recoverability and feedback and recyclability (to producers and assemblers) • Target satisfaction (purity) • Impact of substances on the environment, human health, and safety • Material composition reports • Quantity of raw materials recycled • Compliance with environmental and safety standards • Traceability information (how materials are processed)
Secondary materials market	<ul style="list-style-type: none"> • Quality specifications satisfaction • Target satisfaction (purity) • Material composition reports • Quantity of raw materials recycled • Traceability information (how materials are processed) 	<ul style="list-style-type: none"> • Quality and purity of recycled materials • Quantity of available recycled material • Pricing • Sustainability certifications
Module disassembler	<ul style="list-style-type: none"> • Manual for the disassembly and dismantling of the battery pack • Wiring diagram 	<ul style="list-style-type: none"> • Battery status • Different components' health after the disassembly process • Disassembly procedures

	<ul style="list-style-type: none"> • Exploded view diagram • Part numbers for components • Safety measures/instructions • Hazardous components • Disassembly sequence • Type and number of fastening techniques to be unlocked • Tools required for disassembly • Amount of cells used and layout 	
Module diagnoser	<ul style="list-style-type: none"> • Safety measures/instructions • Hazardous components • Amount of cells used and layout • Data about the original module's SoH 	<ul style="list-style-type: none"> • Module's SoH • Performance testing • Assure the absence of chemical and physical damage absence • Module classification
Cell disassembler	<ul style="list-style-type: none"> • Manual for the disassembly and dismantling of the battery module • Wiring diagram • Part numbers for components • Safety measures/instructions • Hazardous components • Disassembly sequence • Type and number of fastening techniques to be unlocked • Tools required for disassembly • Number of cells used and layout 	<ul style="list-style-type: none"> • Battery status • Different components' health after the disassembly process • Disassembly procedures
Cell tester	<ul style="list-style-type: none"> • Status and characteristics of the original product 	<ul style="list-style-type: none"> • Cells' health status

	<ul style="list-style-type: none"> • Required geometry and chemistry specifications 	<ul style="list-style-type: none"> • Benchmark with the original characteristics • Status and characteristics of the new product
Module reassembler	<ul style="list-style-type: none"> • Spare parts addresses • Module performance and safety requirements and specifications • Required design and specifications • Location and concentration range of hazardous substances. 	<ul style="list-style-type: none"> • The same information provided by the module manufacturer at the first life cycle is to be included in the new DPP • Reassembly procedure
Module certifier	<ul style="list-style-type: none"> • Required safety, performance, and regulatory standards • Previous testing and reassembly records 	<ul style="list-style-type: none"> • Module status and health • Safety and reliability of remanufactured or reassembled modules • Quality requirements satisfaction
Pack reassembler	<ul style="list-style-type: none"> • Required safety, performance, and regulatory standards • Cell and module specifications • Required design and specifications 	<ul style="list-style-type: none"> • Battery status • The same information provided by the pack manufacturer at the first life cycle is to be included in the new DPP • Reassembly procedure • Exploded view diagram
Second-life OEM	<ul style="list-style-type: none"> • Demand forecast excluding recycled materials quantities. 	<ul style="list-style-type: none"> • Battery status • New battery's DPP based on the information provided by the previous actors • Reference to the old battery's data
Logistics operator	<ul style="list-style-type: none"> • Specifications to determine handling requirements • Safety measures (e.g., fire-proof) • Laws of the country in which it operates 	<ul style="list-style-type: none"> • Battery status • Impact of substances on the environment, human health, and safety • Truck conditions during the travel (e.g., temperature)

		<ul style="list-style-type: none"> • Issues or accidents during the distribution • Battery carbon footprint per distribution stage
Battery charging station		<ul style="list-style-type: none"> • Energy consumed per charging session • Charging speed and duration (understand the infrastructure and how much time the car must be motionless) • Source of electricity (renewable or not) • Emissions data (e.g., CO₂ per charge) to compute the carbon footprint) • General data about the status of the charging station to ensure maximum performance • Driving behaviour suggestions

Two additional entities not present in the value chain (Figure 4.1) are included. The first one is the logistic operator, who is the actor moving the goods among other stakeholders. Indeed, it is responsible for the physical flow, from the raw materials to the final products, EOL products, and all the waste or EOL components.

The second entity is the battery charging station, because, although it is not a stakeholder, it could enrich the information exchange through the integration of sensors and databases. The benefits of this integration are enormous, as it can offer real-time data about the environmental factors to which the battery is exposed, the driver's habits, and the recharging characteristics and performance. It could display information for the end-user about the EVB status and driving behaviour suggestions to increase the battery lifecycle, as well as the charging range.

It is important to remember that the OEM may also import goods from non-EU nations where environmental laws and DPP requirements are not applicable. In that particular instance, the OEM must obtain and supply extra information in addition to that listed in Table 1:

- Input data: safety records, test results, quality standards, environmental impact data, and provenance and traceability data (raw material source, refinement method, and ethical sourcing).

- Output information: detailed compliance reports, product origin traceability and environmental impact, integration with local recycling programs, and supply chain transparency reporting.

Given the current situation, the modularity representation in the DPP is feasible only if the actors provide the needed voluntary data, not required compulsorily according to the existing regulations. To avoid this variability, the provision of this data should become compulsory.

Additionally, the DPP must be dynamic to accurately represent the battery's evolution. For this purpose, the integration with the BMS is fundamental. Other systems might be utilised; for example, the battery charging stations should be supported by information systems and databases to supply data about the energy consumed per charging session, as well as the charging speed and duration. Moreover, this dynamic data necessitates the computational ability of the DPP integrated system to evaluate average data and battery conditions across the different stages of the lifecycle.

Besides physical and information flows, the battery value chain is defined by a business flow, which is the combination of contractual and financial exchanges that govern the interactions between stakeholders. Contracts between OEMs and suppliers for cells, modules, and packs, supply agreements between miners, refiners, and component manufacturers, leasing and warranty models that accompany the use phase, and the business dynamics of the secondary market for EOL batteries are all part of this flow. In this post-use phase, collectors, second-life OEMs, and recyclers can purchase and sell batteries, creating new value recovery opportunities. Additionally, the loop is closed by the secondary market commercialisation of recovered materials, which creates more economic value and lessens reliance on virgin resources. As transparency on technical, environmental, and traceability becomes a prerequisite for enabling safe, standardised, and compliant transactions, this business flow tends to integrate more and more with the information flow, since the introduction of the DPP.

4.1.2. DPP-Centric Value Chain

In the context of realising the Digital Product Passport for batteries, it is essential to identify all stakeholders involved and their specific roles within the value chain related to DPP creation and implementation. As highlighted in the Chapter above, all stakeholders interact with the DBP.

Besides the battery value chain, an additional one has been developed 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, observable in Figure 4.7. This is fundamental to understanding the actor's role along the DPP. The DPP-centric value chain builds on the previously mapped battery value chain by shifting the focus from material and information flows in general to the specific roles that actors play in the lifecycle of the Digital Product Passport. Each stakeholder is therefore positioned not only as part of

the physical or regulatory chain, but also as a contributor or user of DPP data at different stages of the battery lifecycle.

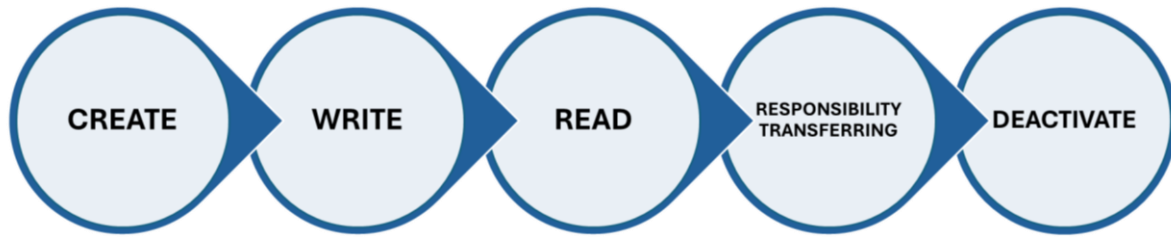


Figure 4.7: DPP lifecycle

The responsibility for the DPP is covered by the Responsible Economic Operator, any entity who is subject to obligations in relation to manufacture, preparation for reuse, preparation for repurposing, repurposing or remanufacturing, making available or placing batteries on the market, including online placing, or putting of batteries into service in accordance with the EU Battery Regulation (Article 3, 1(22)) [16]. Considering this REO's definition, it is assumed that the OEM, the battery remanufacturer, and the second-life OEM usually cover this figure.

During the creation phase, the primary responsibility lies with the OEM or the actor placing the product on the market, who is the economically responsible party. The REO utilises data from component producers, cell manufacturers, and module and pack assemblers. After creating a unique identifier, the OEM generates the DPP, which includes both mandatory and voluntary data, makes it accessible and available, and registers the information in the EU registry. This stage requires the action of public authorities to verify and validate the data and documents. At this stage, the DPP Service Provider also plays a role. [92]

In the case of remanufacturing, the remanufacturer has the right to create and write the DPP of the remanufactured product. When the battery and the respective product are manufactured and then placed on the market by an importer, the importer is responsible for creating the battery DPP.

The writing phase is performed at different levels of the battery's lifecycle, as it can be undertaken by all actors directly involved in the product, including repairers, manufacturers, remanufacturers, testers, and recyclers. In particular, the first writing, at the creation stage, is carried out by the OEM, who can update it anytime; repairers must update the DPP every time maintenance has occurred; collectors and testers must write the test results valid for the second-life decision-making; the reuser updates the battery's reutilization, and, finally, the recycler specifies the recycling details and the no-more existence of the product [92]. Moreover, other actors can update the document with additional and voluntary information. For example, the disassemblers can upload the disassembly process, which may be helpful for assemblers and designers in implementing design-for-disassembly strategies.

During the reading phase, all the actors handling and engaging with the product must have access to the information at different levels based on their roles and authorisations [92].

Deactivation may be necessary on various occasions, such as when a product is no longer available and its components are utilised in a new product, or when the product has been recycled. Indeed, the actors able to deactivate the DPP are those guiding the product through its last phases of the lifecycle or the REO, as they have direct responsibility over the product and the DPP.

A specific example is the responsibility transfer, which occurs when a new company assumes ownership of a product. In this scenario, the initial REO transfers the responsibility from the DPP to the new owner without the need to create a new document. Specifically, two specific situations require the responsibility transferring: (i) the battery has been subject to preparation for reuse, preparation for repurposing, repurposing, or remanufacturing, and is then considered a new product; (ii) the battery status changed to “waste” and, in this second case, the responsibility is transferred to the producer, a producer responsibility organization (according to the EPR), or a waste management operator. [34]

The modularity of the battery must be represented in the value chain through the integration of data related to cells and modules during its creation and writing phases, enabling other actors to access it during the value chain phases associated with that level of modularity.

It is essential to highlight that, if the DPP modularity is pursued, the roles will change. Indeed, cell and module manufacturers should become the REOs of cells and modules, consequently playing a role in the creation of DPPs. This aspect would increase the complexity from technological, regulatory, responsibility, economic, and operational perspectives.

This representation complements the original value chain by clarifying how the DPP distributes responsibilities, supports interoperability, and creates a structured data backbone across all phases. As such, the DPP-centric value chain explicitly connects the structural mapping to the thesis objective, showing how the integration of DPP roles can enable traceability, standardisation, and second-life opportunities.

4.2. Decision Support System

Decision Support Systems (DSS) are “information systems at the organisation’s management level that combine data and sophisticated analytical models or data analysis tools to support semi-structured and unstructured decision making.” [93]

A Decision Support System (Figure 4.8) has been developed to automate and improve decision-making processes regarding EOL EV battery management. Thus, it is possible to reduce uncertainty while enhancing the transparency and efficiency of operations.

- Market demand required for the design of new battery packs in line with the current needs
- Recycling costs and raw material prices to sort packs, modules, and cells to maximise the economic return and define the most suitable recycling process, computing the differential costs
- Technical and performance requirements of batteries in different applications
- Environmental requirements, especially in the case of battery implementation in companies with sustainable goals and regulations
- Quality requirements of different applications
- Target capacity for the module and pack reassembly
- Sorting standards
- Testing standards to benchmark results with required values in different applications.

Through this database, actors can make more effective decisions by having an instant and updated source of information relevant to comparing different alternatives, such as remanufacturing and recycling, and identify the best second-life opportunity based on both economic and environmental benefits. In this way, it is possible to exclude batteries that don't meet not only the defined characteristics (safety, State of Health, etc.) but also the market requirements.

Input

The DSS input comprises physical and information factors, respectively, EOL batteries and supporting data.

The DSS's primary data are obtained through information available in the DPP, BMS, and external database. The DPP retrieves static data, which includes material content, raw material origin, declared carbon footprint, technical production parameters, and historical battery status information. Conversely, dynamic data, including operating temperature, charge-discharge cycles, state of charge, and internal resistance, is delivered to the BMS either in real-time or periodically. Finally, the external database contains economic parameters, such as updated prices of recycled raw materials, market benchmarks for energy storage applications, Environmental, Social, and Governance (ESG) indicators, and technical values useful for computing and defining the best second-life application.

A strong data foundation for decision-making is provided by the integration of the inputs, which enables the DSS to traverse technical, economic, and environmental aspects.

Output

The output generated by the DSS encompasses a variety of technical and decision-making outputs to optimise battery management, in conjunction with the SLB system. The results represent accurate recommendations on second-life opportunities that best

suit the specific conditions of the battery evaluated in the battery-digital passport process, comprehensive and accurate updates to the data contained in the DPP to reflect the current status and changes made accurately. Additionally, it provides precise determination of the battery's current residual economic value, estimates the remaining useful life, and technical and safety compatibility reports for reuse, as well as accurate documentation and operating procedures.

In terms of physical output, there could be both SLB systems and recycled material, based on the selection of the most suitable R-strategy considering the battery's characteristics and market demand.

Control

The controls represent the set of constraints and conditions ruling data processing. They include the European regulatory framework, particularly the Battery Regulation and the ESPR, which establish mandatory requirements for traceability, recycled content, and carbon footprint. Additionally, there are technical standards (e.g., testing procedures, performance parameters, and safety criteria) and ESG guidelines that guide choices towards more sustainable solutions. The regulations and specifications contain safety measures and instructions, transportation regulations, installation instructions, application standards, procedures, recycling rules, and material grade and recovery targets. Lastly, the calculated values are benchmarked using the external database.

By preventing disparities between various actors and encouraging a strategy in line with the goals of the circular economy, controls guarantee that the outcomes generated by the DSS are compliant and verifiable.

Resources

Resources (or mechanisms) encompass the tangible and intangible elements that enable the DSS to function effectively. From a technological perspective, resources include DSS software, calculation algorithms for estimating residual value and technical assessment, digital interfaces that enable data access and visualisation, and links to external platforms. From an organisational point of view, resources also include actors in the value chain (diagnosticians, recyclers, second-life OEMs, logistics operators), who provide, update, and validate data at different stages of the life cycle. From this perspective, resources are not limited to technical infrastructure, but also encompass the set of distributed skills and responsibilities that ensure the correct population and utilisation of the system.

4.2.1. Structure

The DSS developed in this thesis has a structure specifically designed to accurately reflect the configuration and logic of the battery value chain, integrating fully with the

DPP. This system is structured according to the information and operational flows defined in the value chain.

Each phase of the DSS corresponds to specific operational post-use phases of the value chain, as illustrated in the system structure itself: from the receipt and initial characterisation of the batteries, through technical evaluation to identify the best second-life application, to the management of the reassembly, reuse, or recycling process. This alignment ensures circular resource management, maximising the residual value of batteries and significantly reducing the overall environmental impact.

In addition, the DSS structure must encompass a range of cross-cutting activities, including the continuous collection of up-to-date performance data, the maintenance of information contained in the DPP, and the generation of new digital passports in the event of battery reuse or remanufacturing. This ensures that every decision made by the system is based on accurate and up-to-date data, further contributing to the transparency and sustainability of the entire value chain.

The DSS node-tree and the parent diagram (A0) are available in the Appendix A.

The first DSS function is the collection and testing of EOL batteries. Once collected, they are tested using algorithms and specialised testing equipment, supported by a Database Management System (DBMS) and the BMS integration mechanism. The output of this first stage (A1, Figure 4.9) are the test results and the division into reusable, remanufacturable, and recyclable batteries, based on the evaluation done.

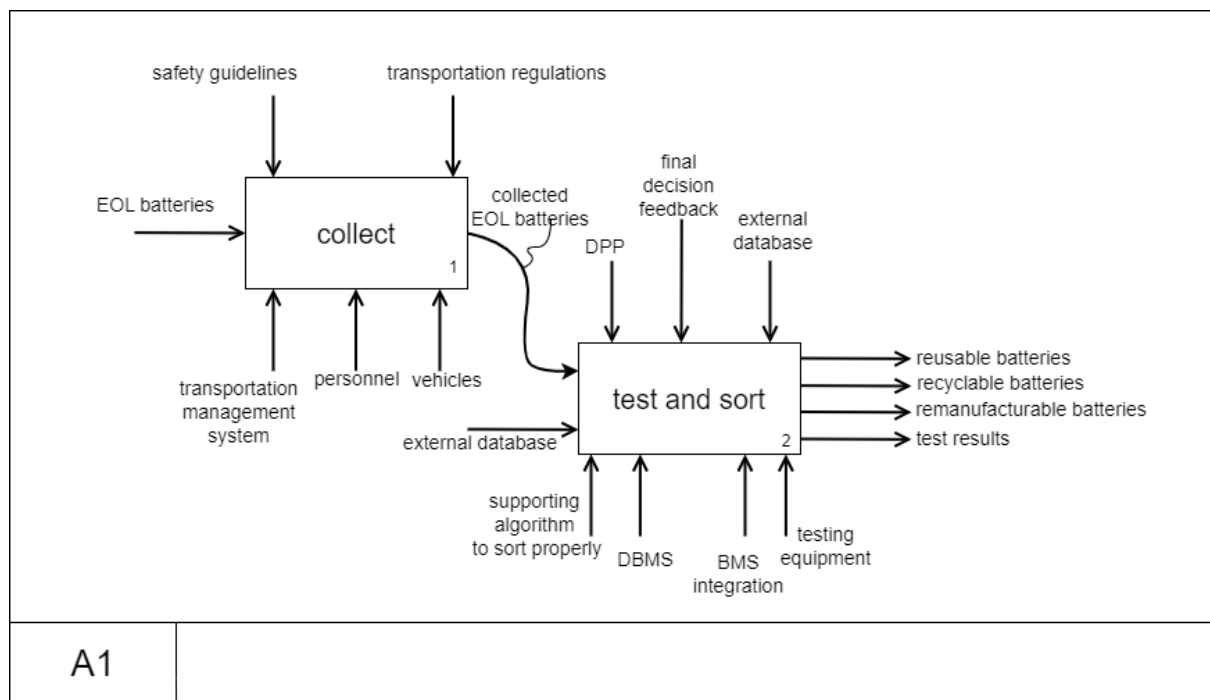


Figure 4.9: DSS - A1

Particularly, the process should start with the verification of the presence of physical damage and harmful substances, which must be avoided entirely for environmental and social (human health) reasons. If they are present, the battery must be recycled properly. The entire testing phase must be based on comparing the battery's value with the market requirements, as contained in the external database, and safety thresholds.

The reusable batteries are reintroduced to the market, and the recyclable ones undergo the recycling function (A4), which produces recycled materials using recycling systems and material pricing systems.

The remanufacturable batteries are remanufactured (A2, Figure 4.10) following the two main steps.

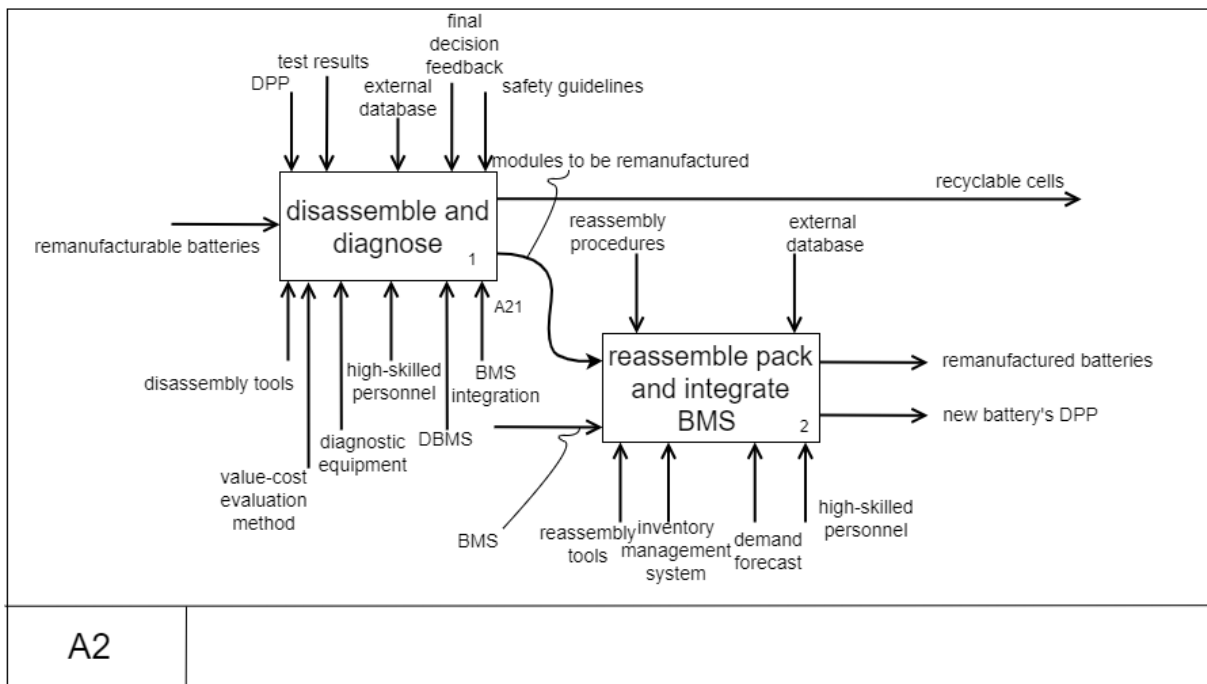


Figure 4.10: DSS - A2

Firstly, the battery is disassembled into modules, and, if necessary, according to a technical evaluation, into cells that are diagnosed and further sorted into remanufacturable and recyclable components. The technical evaluation function also updates the DPP with the possibility of second-life applications, which is then valuable for the economic evaluation function. This first step utilises disassembly tools, diagnostic equipment, value-cost evaluation methods, DBMS, and BMS integration to extrapolate data from the BMS; additionally, all the data, safety guidelines, and test results previously executed are fundamental controls since the disassembly is a complex and manual task, and the diagnosis requires high accuracy. Secondly, the remanufactured modules or cells are reassembled into packs, and the BMS is integrated. This step is completed using reassembly tools and inventory management systems, as well as demand forecast instruments, to supply batteries in line with the

market's current and future demand, and to minimise and manage inventory shelf life. At this point, a new DPP is created for the remanufactured product.

The full disassembly and diagnosis process is observable in the Figure 4.11.

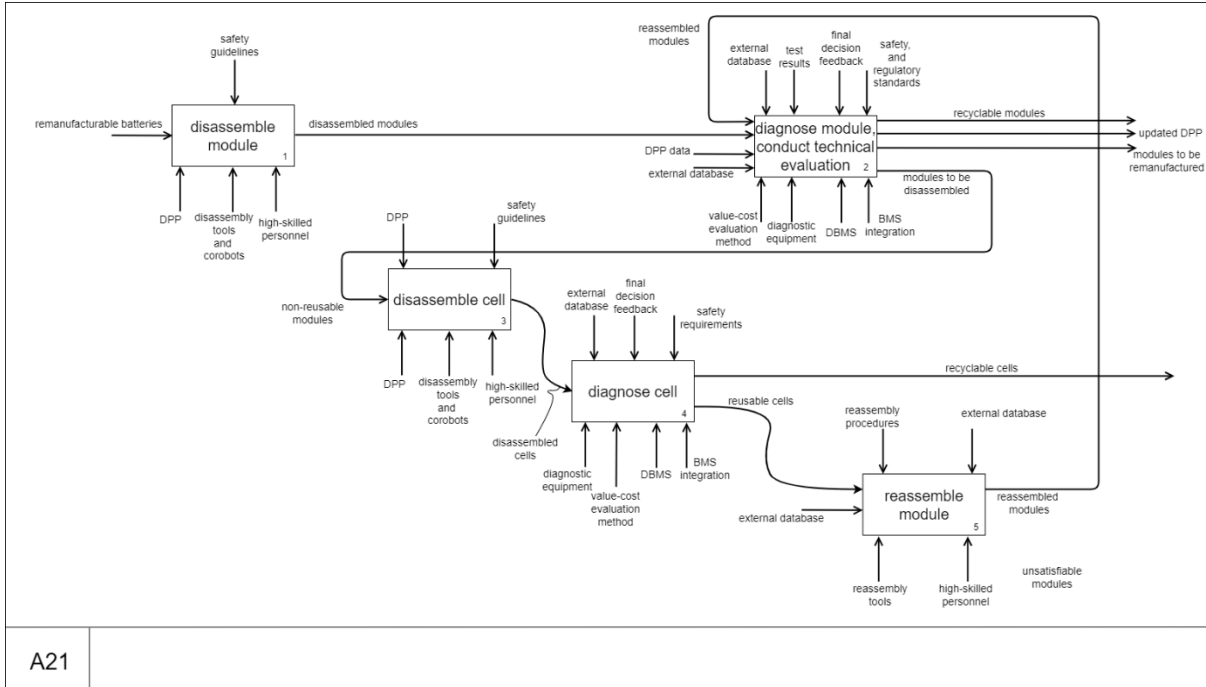


Figure 4.11: DSS - A21

It is essential to underline that the sorting after the diagnosis must be carried out by the DSS, considering the complex combination of mechanisms that causes the battery degradation [63], but also environmental factors like driving and charging behaviours and other data that can be collected and stored by battery charging stations, as proposed in the value chain development.

In the end, the remanufactured batteries, updated DPP, external database, and economic evaluation data pass through a third function constituted by two phases (A3, Figure 4.12).

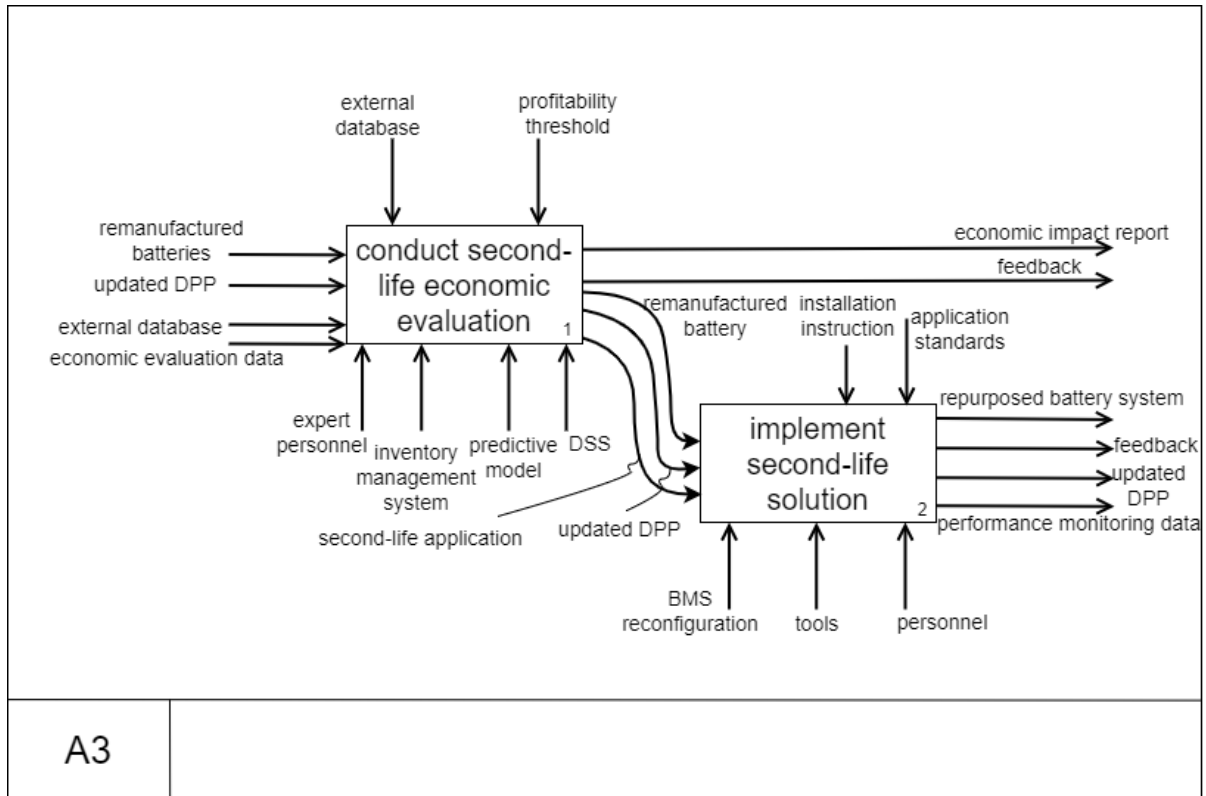


Figure 4.12: DSS - A3

Primarily, a second-life economic evaluation is carried out to determine the final second-life application. This is done by expert personnel utilising inventory management systems, DSS, and predictive models, and controlled by the external database and profitability thresholds. Lastly, the second-life solution is implemented by checking installation instructions and application standards and employing tools and BMS reconfiguration. The final output of this last function is the repurposed/remanufactured battery system, the updated DPP, and performance monitoring data of the new product. Moreover, feedback containing the final decision is sent to some of the previous functions – testing and sorting, module diagnosis and technical evaluation, and cell diagnosis – to continuously improve and optimise the process and the DSS.

The DSS should be dynamic, given that the context is highly variable in terms of specification values for new products due to continuous innovation in this sector. Additionally, batteries returned from their first use can have varied usage histories and characteristics.

The connection between the DSS, the DPP, and the BMS must be guaranteed. Indeed, the BMS should be able to compute the RUL at the pack, module, and cell levels to enable remanufacturing at different modularity degrees, since, as previously specified, whenever a battery pack is unsuitable for remanufacturing and must be recycled, it is opportune to analyse the single battery modules. Again, data at different granularity levels are fundamental.

4.2.2. Link Actors – Functions

The link between the DSS functions and the actors in the value chain is clearly reflected in the integrated structure of the system, where each function represents a specific actor in the value chain, facilitating the smooth and transparent management of the battery life cycle.

For example, access to DPP and BMS data is primarily managed by diagnostics and second-life OEMs, who perform technical assessments and identify the best opportunities for reuse. These players perform precise compatibility and performance evaluations using information supplied by OEMs and initial manufacturers, including technical specifications, materials, and usage history.

Diagnosers, second-life OEMs, and remanufacturers are among the stakeholders involved in the DPP update function, which tracks the battery's current condition and potential reuse. In particular, the role of the remanufacturer is fundamental in the process of reassembling and testing batteries for a new application, thus generating new digital passports that accurately reflect the updated conditions of the products.

Functions related to residual value and residual life cycle assessment involve actors such as diagnosers, repairers, remanufacturers, and recyclers, each with specific responsibilities in determining the economic and technical opportunities for reuse or recycling. Recyclers use the available information to determine the value of recycled raw materials and ensure that the recycling process meets high-quality standards.

This direct link between DSS functions and actors in the value chain ensures that all decisions are based on accurate and up-to-date data, thereby promoting efficient, transparent, and sustainable battery management throughout the value chain.

Additionally, to ensure the effective and efficient implementation of the DSS, stakeholders must provide the necessary data at each step and make a decision simultaneously.

4.2.3. Benefits

The application of an intuitive and standardised DSS could incentivise the reuse and remanufacturing of EOL batteries, which are currently recycled due to, among other factors, a lack of information and data.

The DSS's ability to communicate with all parties involved in the value chain and serve as a tool for transparency and coordination is one of its unique features. A safer, more sustainable end-of-life battery management model focused on optimising residual value is promoted by the more effective and less arbitrary interaction between technical and economic decisions.

From a comprehensive perspective, the DSS generates benefits across three levels: economic, environmental, and social.

Economically, the DSS lowers testing and diagnosis costs by using certified data from the DPPs and BMSs. By removing the need for manual verification, standardised data accelerates the battery classification and assessment procedures. Furthermore, secondary market operators are more confident due to the system's ability to precisely estimate the RUL of batteries, promoting the growth of transparent and competitive commercial channels. This results in more sales opportunities for second-life OEMs and higher economic returns for battery owners.

From an environmental perspective, DSS promotes more efficient use of resources by directing batteries to the most appropriate second-life solution. Reduced classification errors and greater accuracy in defining reuse or remanufacturing opportunities prevent the premature recycling of batteries that are still usable, resulting in savings in critical raw materials and reduced emissions associated with the production of new cells. In addition, the ability to accurately track material flows contributes to achieving sustainability goals and maximises circularity throughout the supply chain.

Socially speaking, the DSS fosters openness and confidence among end-users and various value chain participants. At the same time, process standardisation reduces operational risks for workers involved in transportation, disassembly, and collection, improving safety conditions. Lastly, the system may help regulatory bodies monitor regulatory compliance and encourage the adoption of best practices across the supply chain.

The safety aspect is particularly relevant because, unlike the economic and environmental benefits of EOL batteries management, safety concerns have received less attention in circularity [6]

4.3. Use Cases

The objective of this chapter is to introduce a series of realistic and operational use cases that demonstrate the potential of the DPP and DSS in enabling key functions along the battery value chain. Their purpose is to demonstrate how the DSS can be effectively used in real-life scenarios, integrating regulatory requirements and DPP-enabled data into decision-making processes. In this way, the use cases serve as both illustrative examples and demonstration tools, showcasing the system's usefulness in supporting second-life opportunities for batteries.

The represented scenarios encompass various stages, from second-life reuse to safe dismantling and monitoring of anomalies, and always emphasise circular practices and strategies.

Each use case has been developed according to a structured methodology based on the analysis framework provided by the Battery Passport Value Assessment document [54], utilising the UML tool, as described in the chapter 3.3. Additionally, each case has

been adapted to ensure consistency with the value chain and the described in the previous paragraph.

The employed approach allows each scenario to be analysed independently and also provides an understanding of the interconnection among the various cases.

Starting from these frameworks and tools, the use cases were selected and developed based on the following criteria:

- Operational relevance: the capacity of the DPP to facilitate or enhance a crucial battery lifecycle activity.
- Value chain coverage: use cases illustrate various value chain phases, with an emphasis on remanufacturing operations.
- Diversity of actors involved: to emphasise the DPP's content accessibility from multiple angles, public authorities, end users, digital systems, and industry stakeholders were included.
- Provable added value: tangible benefits resulting from the use of the DPP in economic, environmental, and social terms.

Use Cases along the Value Chain

To provide an overview of the analysed use cases, a map was created, simplifying the value chain to the relevant phases and representing the key activities of the Decision Support System, showing the positioning of the use cases along the battery value chain. It is possible to understand the complementarity and connections between the different use cases by using this representation, which is seen in Figure 4.13. The use cases listed below have been created:

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

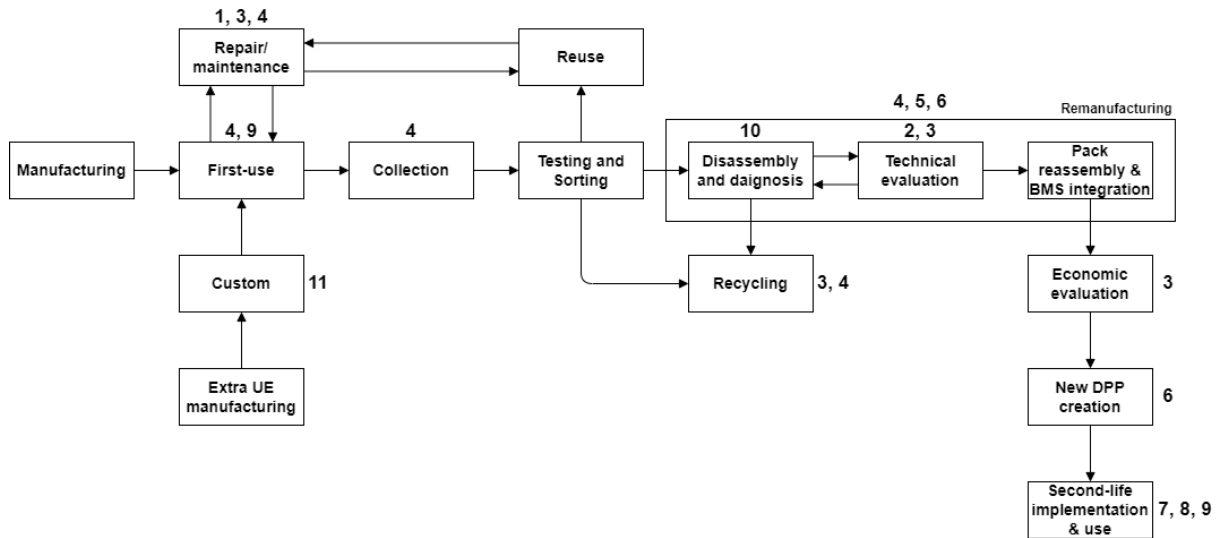


Figure 4.13: Representation of the use cases along the value chain

This map facilitates a systematic reading of the chapter and serves as a visual guide for navigating between the different usage scenarios. Moreover, it highlights areas particularly dense in applications and others where further opportunities can emerge in future studies.

4.3.1. Eased Repair to Extend the Battery Life

In this first use case (Figure 4.14), the DPP's potential to help repair battery packs during their first useful life cycle is examined. This could reduce the need for premature replacements, increase the operational life of EV batteries, and ensure more effective use of resources. In particular, the DPP makes repairs safer, quicker, and easier to trace by offering structured access to diagnostic data, technical information, and OEM documentation.

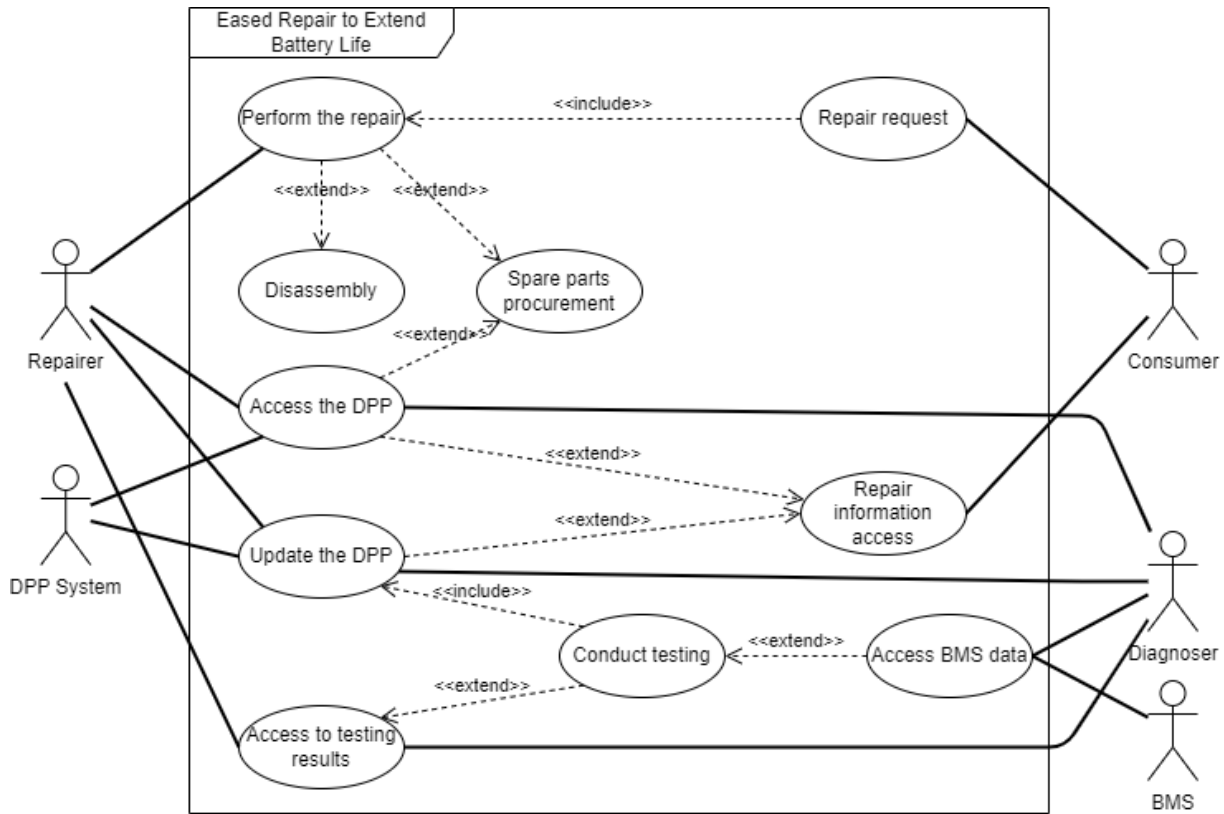


Figure 4.14: UML diagram - eased repair to extend the battery life

The actors involved in this scenario include the diagnoser who conducts testing relevant to the repairer; the latter, who performs the physical intervention on the battery; and the consumer who requests the repair. Moreover, the BMS plays a role in transmitting both real-time and historical operational data related to the battery status. Finally, the DPP system acts as a platform for accessing and updating product information.

The workflow begins with a repair request by the consumer, who can access repair information, including the nearest and compatible repairer information. The actual repair starts with access to diagnostic data from the BMS and DPP, including parameters such as SoH, charge/discharge cycles, operating temperature, and error history. Based on this information, the diagnoser provides and updates test results utilised by the repairer to identify failure patterns and criticalities. Upon completion of the repair, the operator updates the DPP with a record of the repair event, including the date, outcome, and technical responsibility.

For the use case to be implemented effectively, it is assumed that the DPP is accessible to the authorised repairer and contains an up-to-date configuration of the battery pack, OEM manuals, safety instructions, and service history. Additionally, the BMS must be capable of providing reliable diagnostic data, and the repairer and diagnoser must be able to interact with the system to update the pre-service and post-service status.

The essential data for implementing this use case include identifiers and product data, as well as data on circularity, resource efficiency, performance, and durability. Among the voluntary data, instrumental are information and directions about repair and maintenance to increase the product's useful life in the consumer's hand. This data can include precautions, proper charging and discharging suggestions, and other relevant aspects.

The benefits are manifold: from an economic point of view, reduced replacement and repair costs and extended first lifecycle; from an environmental point of view, prevention of premature disposal and lower material usage; from a social point of view, greater post-intervention safety, customer confidence, and transparency towards stakeholders and job creation in the repair sector.

Without the Battery Passport, this use case would not be feasible, or it would be highly complex due to limited access to repair instructions and battery history, as well as lower traceability of previous maintenance and repair actions. The diagnosis would require additional effort and specialised tools. Additionally, consumer access to safety instructions can ensure an extended life cycle and reduce the need for later repairs.

4.3.2. Technical Evaluation to Define the Most Suitable Second-Life Application

This use case (Figure 4.15) represents one of the key functions empowered by the DPP, particularly relevant for operators in the reuse and remanufacturing stages. The primary objective is to support second-life OEMs in identifying, in a structured and data-driven manner, the most suitable secondary application for each end-of-life battery, taking into account its technical condition, residual performance, and the requirements of various market applications.

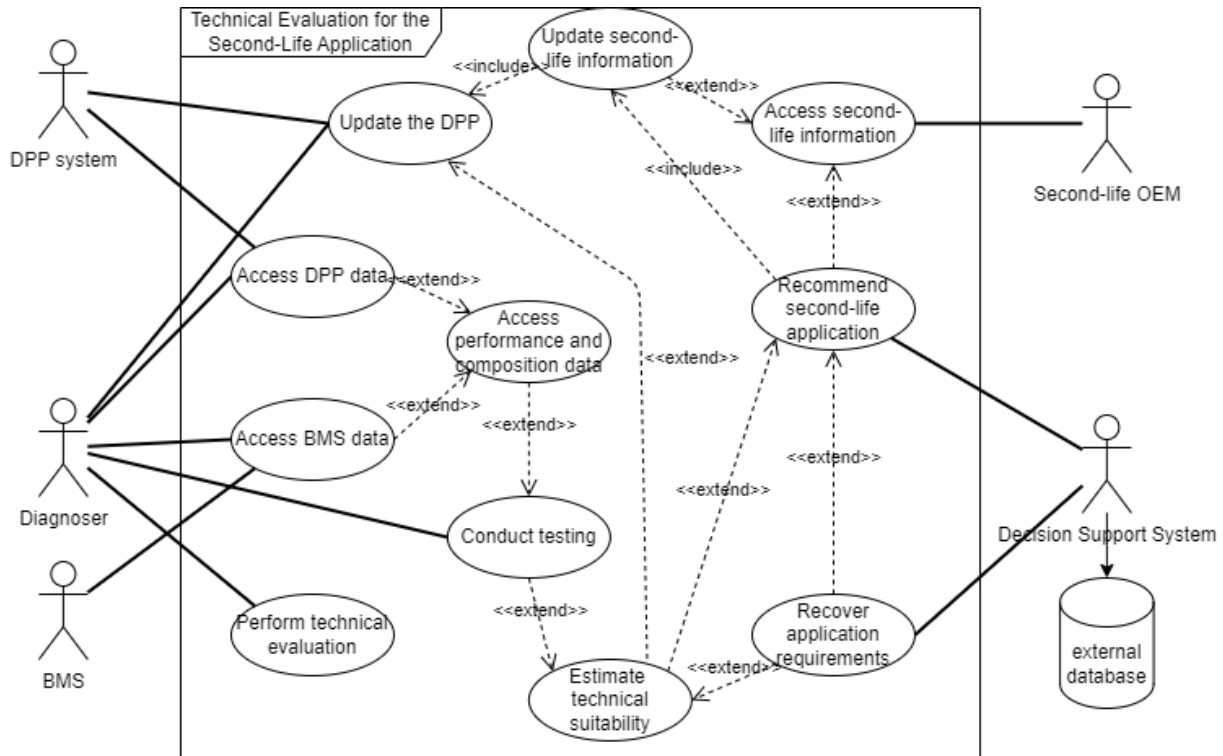


Figure 4.15: UML diagram - technical evaluation to define the most suitable second-life application

The process begins with access to data contained in DPP and BMS systems, such as charge/discharge cycles, operating temperature, health status, and other performance parameters. This information is integrated with performance data recorded in real time or obtained through specific tests conducted by the diagnoser. All these elements enable the diagnoser, supported by the DSS, to estimate the technical suitability of the battery by comparing its status with the performance requirements of various possible second-life applications, such as ESS, light electric vehicles, or other industrial uses, contained in the external database.

Once the analysis has been processed, the DSS recommends one or more secondary applications consistent with the technical characteristics identified. The Second-life OEM receives these recommendations and can then proceed with the implementation of the most suitable solution. Information relating to the identified opportunity, the technical reasons behind the selection, and any limitations encountered are then recorded and updated in the DPP, making them available to those involved in the subsequent stages of the value chain.

In the absence of a DPP, however, the selection of second-life opportunities is based on empirical assessments, manual inspections, and often undocumented assumptions. This leads to greater uncertainty, a higher risk of error in selecting applications, possible waste of resources, and reduced transparency towards supply chain players and end buyers.

Mandatory data required for the technical evaluation include battery materials and composition, circularity information (information on preparation for second-life use), and performance and durability data. The process can be further eased if voluntary and durability data, second-life monitoring data, and a sustainability report are available.

Mainly, the benefits of this use case are economic, including second-life decision optimisation, battery failure reduction, higher residual value, and higher second-life selling opportunities. Additionally, maximising circularity, cutting waste, encouraging safer reuse opportunities, and minimising material usage are all advantages for the environment. Lastly, some social benefits emerge, such as increased transparency in the second-life trade and fewer accidents resulting from fewer battery failures.

4.3.3. Simplified Residual Value Determination

Simplified determination of residual value is a strategic step in assessing the economic feasibility of second-life options for end-of-life batteries. In this use case, the DPP plays a central role as a tool that enables the rapid estimation of the monetary value and remaining useful life of a battery, based on traceable and shared data, and on the second-life opportunity determined in the previous use case. Unlike in-depth technical analyses, the objective here is not to assess the physical condition of the system in detail, but to effectively estimate the economic value that can be recovered through strategies such as repair, remanufacture, or recycling.

The actors involved include the diagnoser, the second-life OEM, the recycler, the repairer, the collector, the consumer, the DPP system, and the BMS; in addition, the DSS integrates data sources to support the estimation. After the collection of end-of-life batteries, the diagnoser accesses the DPP and BMS systems to retrieve historical data on usage and residual performance. Based on this information, the system determines the most economical strategy among reuse through repair, remanufacturing, or recycling, using models integrated into the DSS or internal assessment tools. The battery can thus be directed towards the most convenient path, reducing inspection costs and maximising the overall profitability of the system.

The diagram is observable in the Figure 4.16.

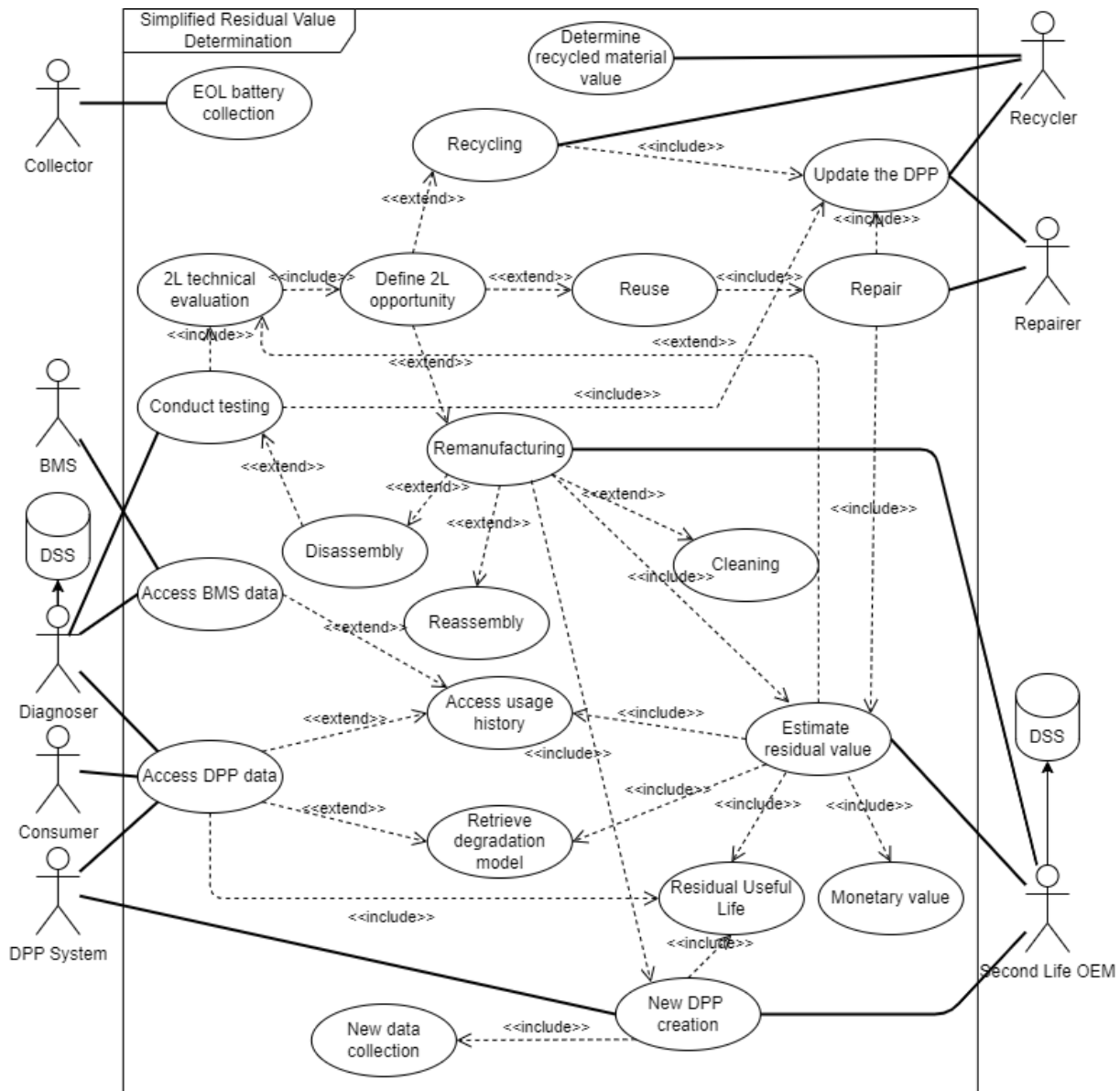


Figure 4.16: UML diagram – simplified residual value determination

One of the key steps is to estimate the residual monetary value, considering parameters such as recoverable materials, intervention costs, and any economic margin that can be obtained from the second life cycle. This process is enabled by access to data on material composition, sourced from the DPP and external sources. The remaining useful life is estimated by retrieving information on usage, known degradation patterns, and operational data, which are also centralised in the DPP or updated through the BMS or supportive new data collection campaigns.

With the DPP in place, this assessment is rapid, digitised, and comparable, with key indicators recorded directly in the new DPP if the battery enters a second life cycle. In the absence of the DPP, however, the process is highly uncertain: the lack of historical data makes it impossible to estimate useful life, strategies are chosen conservatively,

and there is a high probability of sending packs to recycling that could instead be economically valorised.

Mandatory data includes battery materials composition, performance, and durability parameters, and references to the original packaging. Carbon footprint data, as well as recycled content and values previously estimated by other chain operators, are the most pertinent optional data.

The main benefits include reduced testing and diagnostic costs, increased operating margins from data-driven decisions, and the ability to openly communicate to investors and customers the value and potential of each battery collected. Environmentally speaking, it also makes it possible for more second-life applications, which raises resource efficiency and reduces material loss, both of which lower production-related GHG emissions.

The importance of computing SoH and RUL prediction into future pathway decisions is addressed in the literature as well, since it enables the implementation of effective second-life opportunities [70].

4.3.4. Comprehensive Battery Risk Assessment

The overall risk assessment of batteries is a crucial function in ensuring safety during the handling, storage, and transportation of batteries. This use case focuses on integrating data accessible via the DPP to determine the level of risk associated with each battery, based on chemical, electrical, and behavioural criteria. The ultimate objective is to enable the safe and compliant handling and transportation of batteries through risk-based evaluations.

Several actors in the value chain participate in the process (Figure 4.17): the OEM, which provides the initial DPP data and safety guidelines; the diagnoser, which performs assessments and tests; the DPP system, which centralises and distributes information; the logistics operator, who oversees transportation; and, lastly, operators who work with the battery, like repairers, recyclers, or end users. The first step in the process is accessing the DPP's data, which includes technical details, chemical composition, and operational data obtained from the BMS. Moreover, it contains details about previous usage and any further testing.

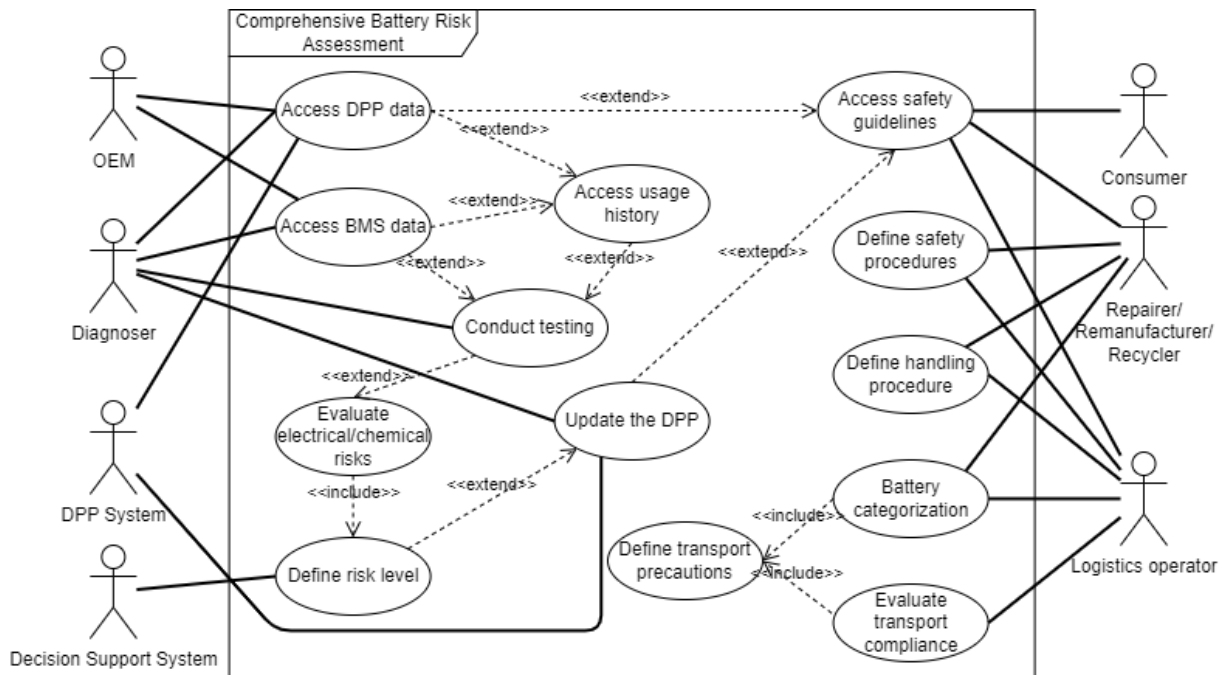


Figure 4.17: UML diagram – comprehensive battery risk assessment

Based on the available data, the diagnoser assesses potential chemical and electrical risks, identifying any hazardous conditions. This makes it feasible to create a risk classification with the DSS's assistance, which is subsequently used to specify the proper handling and transportation safety measures. Identifying batteries that need controlled temperatures, fireproof containers, or particular handling techniques is one example of this. All chain participants can access the results since they are updated in the DPP. To prevent ambiguity and subjective interpretations, all actors can access the updated risk profile and modify their operational actions accordingly. Indeed, they can establish a safety approach, handling procedures, proper battery categorisation, and compliant transportation. Conversely, the absence of the battery passport forces operators to rely on manual inspections, which require more time and resources and increase the risk of classification errors or regulatory violations.

Mandatory data includes general information about the manufacturer and the battery, materials and composition of the battery, as well as technical data on performance and service life. Optional data may include incident reports, maintenance interventions, or new safety tests. The main benefits of this use case include reduced risk and accidents for operators and transporters, simplified regulatory checks, higher safe reuse opportunities, minimisation of pollution from batteries, safer recycling, and, more generally, greater confidence in the safety of processes and transportation throughout the value chain. The logistic and transportation aspects are paramount since they have been identified as key issues, considering especially safety, cost, and regulatory topics [24].

4.3.5. EV Battery Reuse in Energy Storage Systems

As previously discussed, the reuse of EV batteries in ESSs represents one of the most promising opportunities to extend their useful life and maximise the economic and environmental value of the resources used in their production. Additionally, EV batteries that will reach their EOL are forecasted to exceed the battery stationary demand in 2030; indeed, it is expected that a higher number of BESS installations will use [94].

This use case (Figure 4.18) focuses on the deployment of this transition in a safe, traceable, and efficient manner. Thanks to the availability of data contained in the DPP, the actors involved, including diagnosticians, remanufacturers, and second-life OEMs, can access detailed information on the configuration, residual performance, composition, and health status of the batteries.

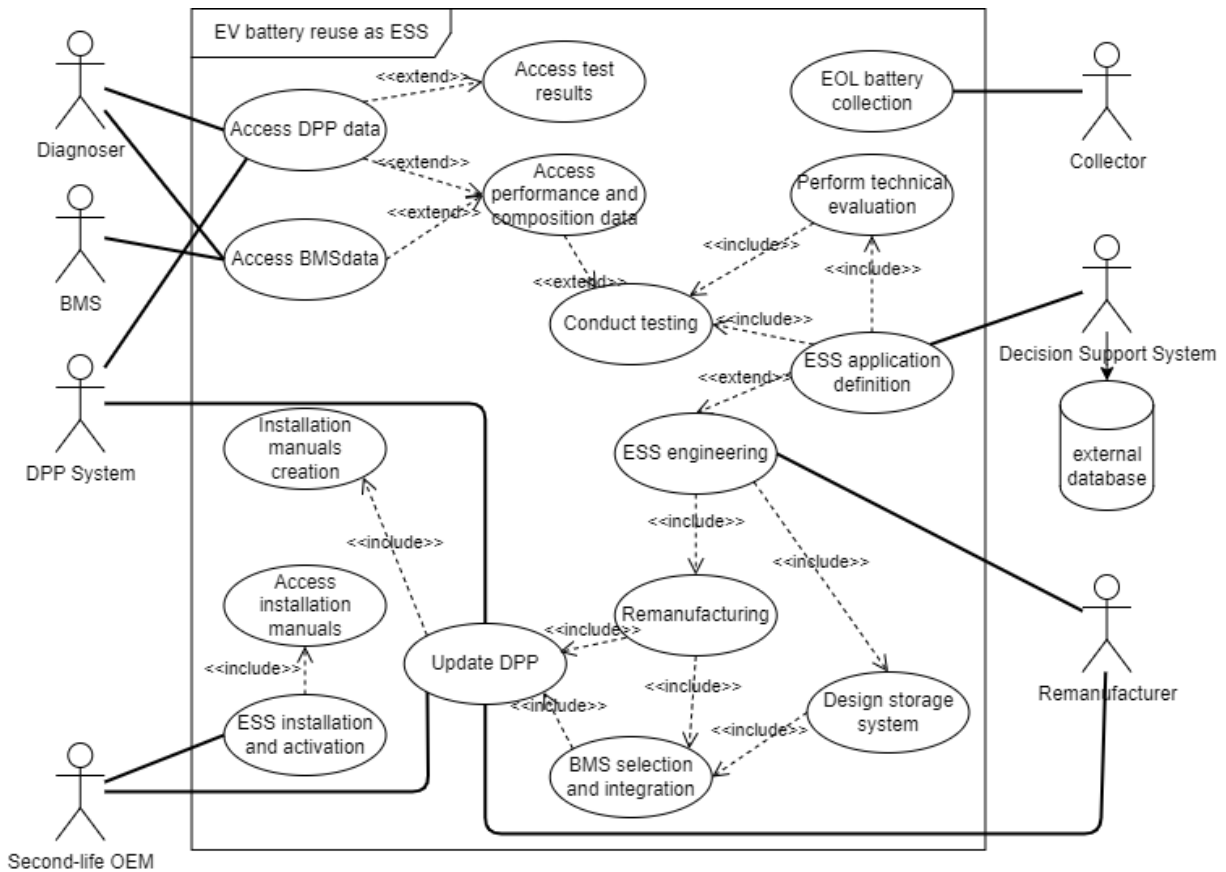


Figure 4.18: UML diagram - EV battery reuse as ESS

This process starts with the collector recovering EOL batteries, followed by a technical analysis that may include electrical testing, BMS check, and comparison with the target ESS application’s specifications. The DSS assists in this step by evaluating the supplied data to determine the technical suitability of the batteries for stationary use and to identify the optimal configuration for the storage system. The remanufacturing process, which includes selecting and integrating new BMS systems, designing the ESS

Stakeholders can obtain information about each module or cell thanks to the availability of DPPs, especially diagnosers, second-life OEMs, and remanufacturers. After that, the data is contrasted with a few units that are compatible with it in terms of technical configuration, health status, and residual performance. The DSS helps define the most suitable second-life application and new battery architecture, suggesting the combinations of modules that best meet the requirements of the target ESS. The remanufacturer prepares the battery according to the design depiction, integrating the selected components. Once the configuration has been defined, a new aggregated DPP is generated by the second-life OEM, clearly showing the traceability of the individual integrated units, data on the expected performance of the complete system, and the link to the original passports.

It is relevant to highlight that this process is feasible if the DPP actually represents the battery granularity, specifically, pack, module, or cell. Otherwise, it is not possible to access and integrate information about all the selected modules or cells without further testing. This aspect has not been systematically defined yet by Consortia and regulations, but it should be addressed. Indeed, without a battery passport, the operation becomes very complex and risky. Selecting compatible modules requires additional testing, and the lack of historical or technical data increases the risk of assembling heterogeneous and potentially dangerous packs. This not only negatively affects the efficiency and safety of the ESS but also compromises its durability and the possibility of intervention in the event of a failure.

The data required to perform the process includes information on battery materials and composition, circularity parameters, and technical data on residual performance. Voluntary data contains historical information on aggregation, service life, and previous uses. The advantages of this approach are manifold: it reduces testing and validation costs, maximises the reuse of batteries that are still valid, improves the quality of second-life ESS, enables system modularity, and improves safety both during assembly and subsequent use.

4.3.7. Circularity Impact Computation

To show that remanufactured batteries are environmentally competitive, to build their credibility, to gain stakeholder acceptance, and to meet sustainability and regulatory goals, it is essential to measure the environmental performance and value of SLBs from a circularity perspective. This use case (Figure 4.20) aims to compute the avoided impacts compared to producing a new battery or recycling, providing circularity indicators that can be made transparent and comparable.

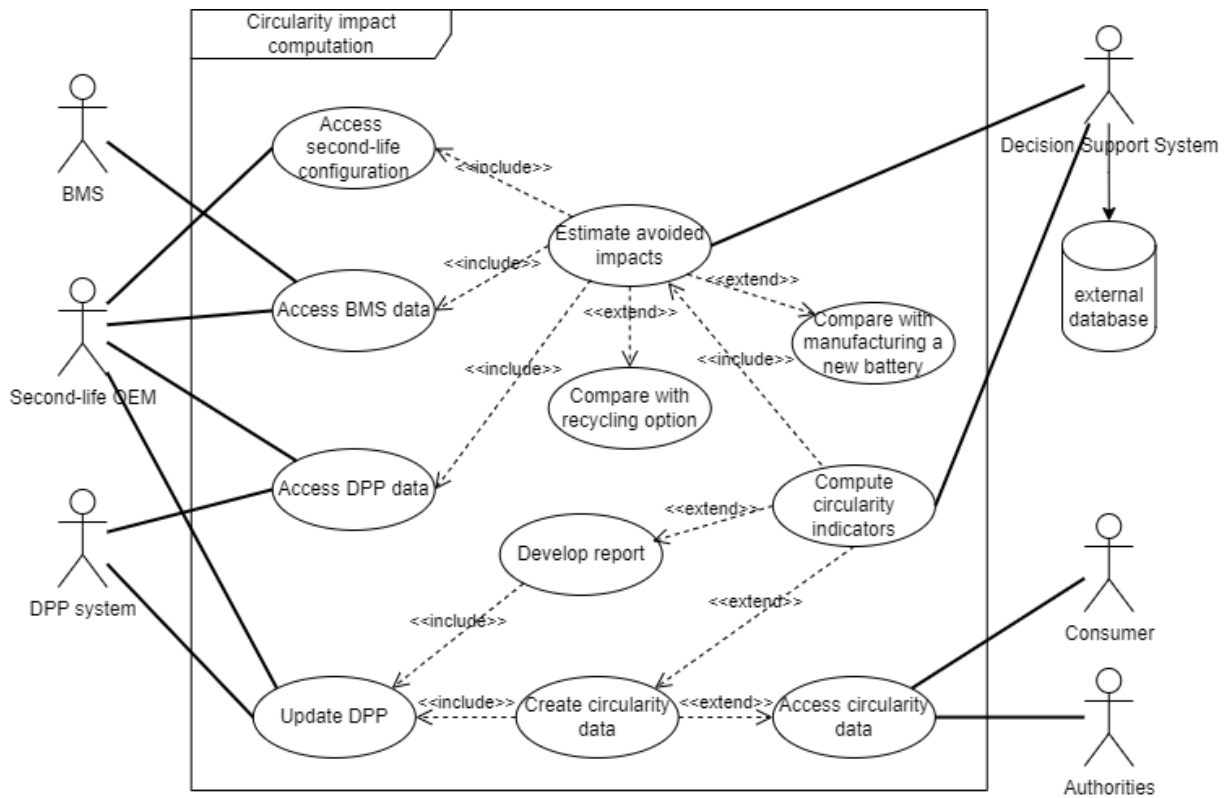


Figure 4.20: UML diagram - circularity impact computation

The linkage between the DPP and the DSS provides access to data on the second-life configuration, the technical properties of the BMS, and historical data stored in the DPP. Due to its integration with external databases, the system can estimate the environmental impacts associated with the production of new batteries and their recycling, comparing them to those of the second-life configuration. Circularity indicators, which show resource efficiency, amounts of repurposed material, reductions in CO₂ emissions, and other environmental savings, are computed from these comparisons. The resulting report is then made available to stakeholders, including customers and regulatory bodies, and included in the DPP.

Mandatory data on battery composition and materials, as well as circularity indicators, are among the data needed for this process. Examples of voluntary data include LCA data, methodological assumptions, and qualitative information from manufacturers and recyclers.

This feature offers a number of benefits, such as making it easier to comply with environmental laws, supporting circularity metrics and climate neutrality goals, and providing access to incentives that are connected to demonstrable environmental advantages. Furthermore, it increases the transparency and social acceptability of second-life products, contributing to the transition towards a truly traceable and measurable circular economy.

4.3.8. Traceability Across Multiple Lives

One essential tool for ensuring openness, risk control, and precision in environmental and circularity evaluations is the full traceability of a battery's life cycle across all its phases of use. This use case (Figure 4.21) focuses on reconstructing the entire history of a battery by coherently linking the various DPPs generated during its successive lives: from initial production to second-life configurations or reconditioned uses.

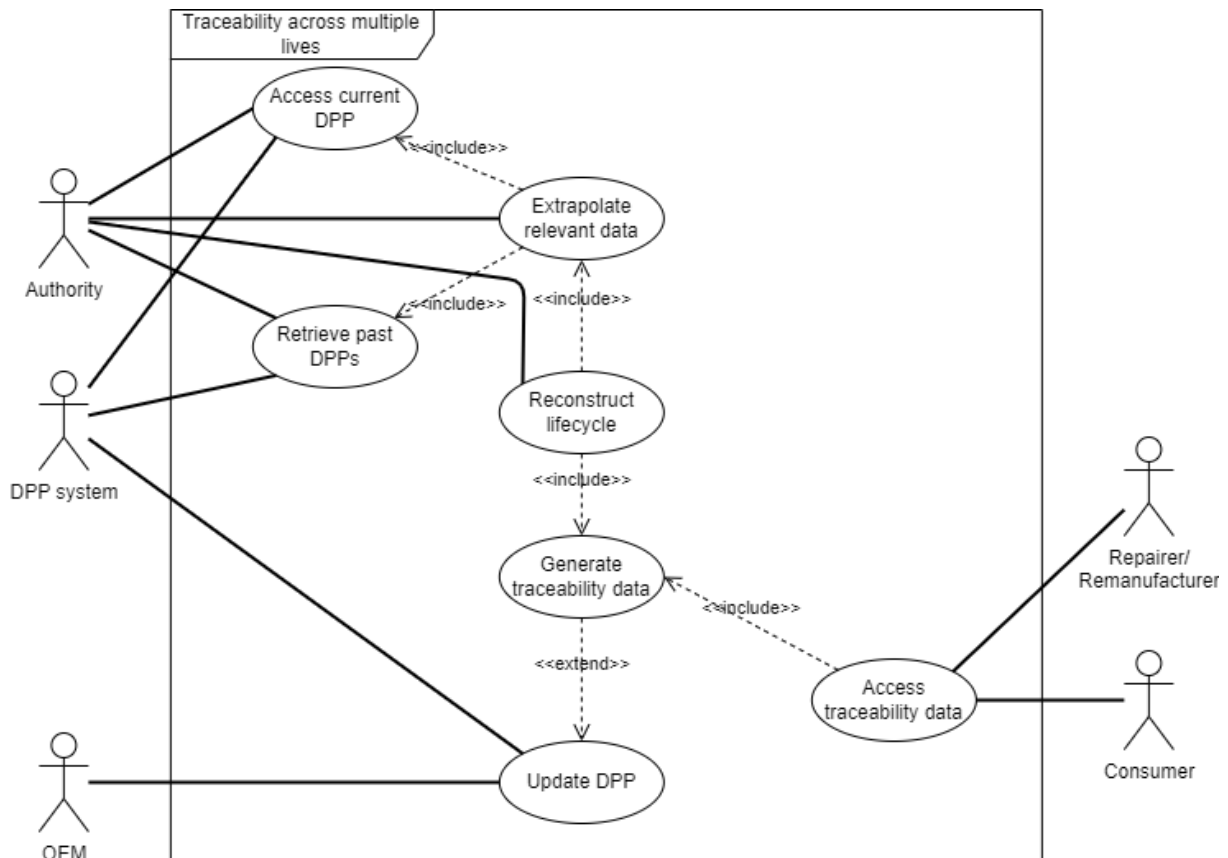


Figure 4.21: UML diagram - traceability across multiple lives

The procedure depends on stakeholders and authorised authorities having access to the most recent DPP and, if available, earlier DPPs. The battery's life cycle can be reconstructed structurally by extracting pertinent data from this chain of information, including the date of first activation, prior applications, the number of cycles, damage, and accidents. This reconstruction enables the generation of a set of traceability data, which is then integrated and updated in the current DPP, making it accessible to repairers, reconditioners, and consumers.

Without a DPP system, this task is almost impossible: the lack of a common standard and the fragmentation of information among the various actors make it extremely difficult to trace the history of a battery beyond its first useful life. Furthermore, key elements are missing to support decisions relating to safety, sustainability, or liability management along the supply chain.

Mandatory data for this process includes unique identifiers and product data, as well as information related to supply chain due diligence. Voluntary data, on the other hand, provides operator identifiers and additional qualitative information collected during the various stages of use and transformation.

Greater traceability improves risk control and system reliability, facilitates more accurate LCA calculations, and improves transparency for all stakeholders involved. In addition, the ability to monitor material and energy consumption across multiple life cycles enables cascading utilisation strategies and supports a truly circular, data-driven model.

4.3.9. Anomaly Detection

This use case (Figure 4.22) makes use of the external database that can be accessed through the DSS to continuously compare data from the BMS with predetermined reference values in order to detect and trace anomalies in real time. One essential component for guaranteeing SLB storage systems' peak performance, user safety, and financial worth is real-time battery monitoring.

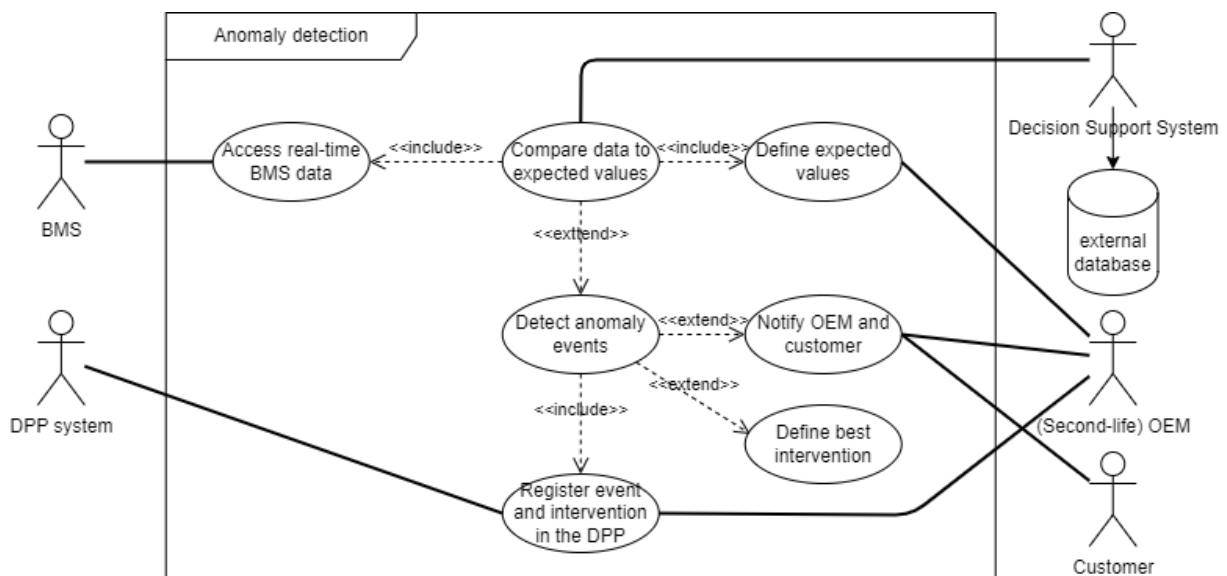


Figure 4.22: UML diagram - anomaly detection

To identify notable deviations, the process begins with access to real-time BMS data, which is then compared with the expected values that the OEM had previously entered into the system. The system creates an event when an anomaly is found, which can be automatically recorded in the DPP to enhance its history. To enable a prompt and focused response, the DSS simultaneously notifies the OEM and the end user. To encourage openness and maximise future maintenance, the recommended corrective action, if available, is also recorded in the DPP.

In the absence of a DPP, however, there is no centralised register of abnormal events, and the diagnosis of malfunctions or battery degradation is less structured. This can lead to economic losses due to premature component replacement, increased risk for

the user, a lack of traceability of interventions, and difficulties in assessing residual value.

Mandatory data requirements include product identification information and real-time BMS data. In contrast, optional data may consist of external environmental data that supports the interpretation of the context in which the anomaly occurred, for example, through data from charging stations.

The advantages of this system are clear: maintenance and repair costs are significantly reduced thanks to targeted interventions; material damage and serious failures are prevented thanks to timely diagnosis; end-user safety is improved, as users are informed in real time; and battery life is increased, reducing cases of early recycling and improving the residual value of the product.

4.3.10. Disassembly Facilitation

This use case (Figure 4.23) eases the battery pack disassembly phase, one of the most critical activities in the preparation process for repurposing, remanufacturing, or recycling. Operators can perform disassembly in a safer, more effective, and traceable manner thanks to the DPP's structured and standardised data, which reduces the possibility of damaging reusable components and improves the quality of material separation.

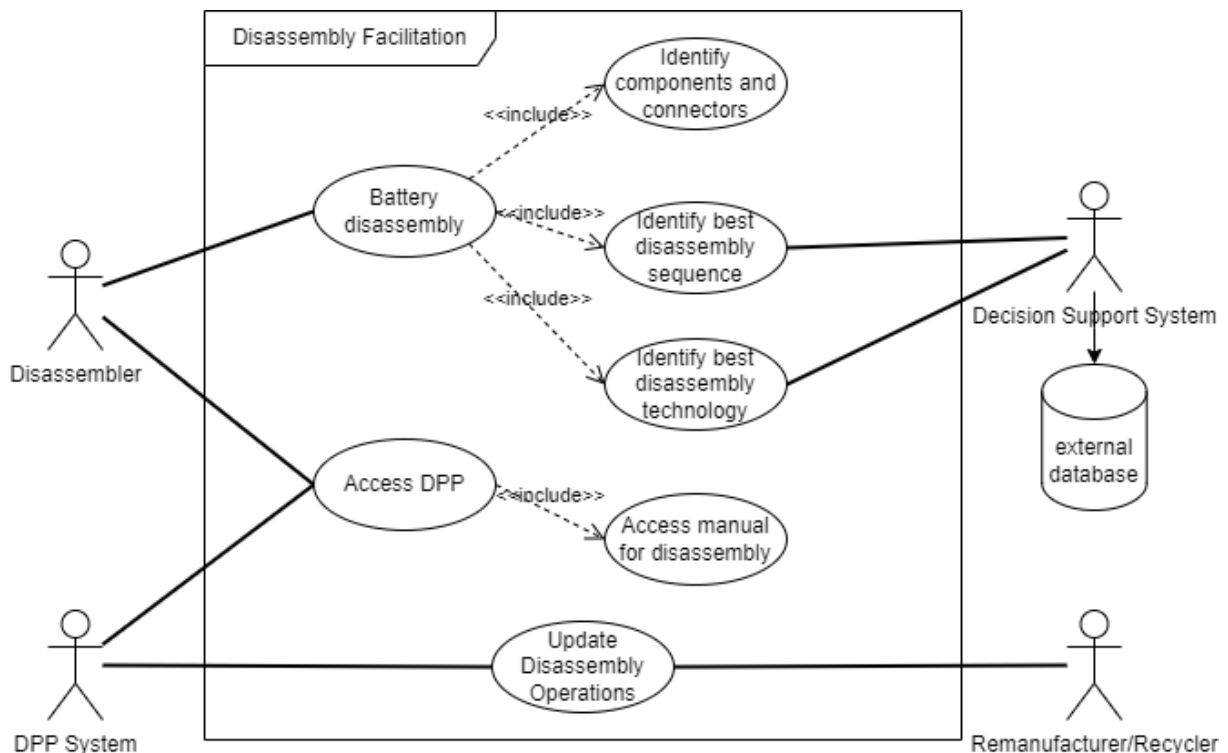


Figure 4.23: UML diagram - disassembly facilitation

The leading players involved are the disassembler, the remanufacturer or recycler, and the DPP system that provides access to the necessary information.

The planned workflow begins with accessing the DPP using the battery identification code. The disassembler then receives detailed instructions in the manual for disassembly on how to open the package, the order in which to remove the modules, and the location of screws, connectors, and critical components. Additionally, the DSS supports the operator in defining the optimal disassembly sequence and technology, as well as accessing and following the manual for correct disassembly. Safety information is also displayed, and suitable tools for disassembly are suggested. During the operation, the disassembler can follow a checklist and digitally record the progress, any anomalies encountered, and the condition of the recovered components. At the end of the process, the DPP is updated to reflect the disassembly, indicating the date, result, and responsibility.

The DPP must include identifier and product data, as well as circularity and resource efficiency data, which should consist of a manual for disassembly. These can be supplemented by optional data, such as detailed instructions, images, videos, torque values, fastening types, 3D diagrams, or exploded views not provided in the OEM's manual. Without the DPP, dismantling is often carried out randomly, resulting in high operational risks, inefficiencies due to the need for manual tests or visual inspections, and a lack of structured documentation on the work performed. The introduction of the DPP, on the other hand, makes the process guided, documented, and more reliable, improving not only operator safety but also the quality of component recovery and preparation for a second life.

In this way, transparency is higher, working conditions are enhanced, and training and standardisation for operators are improved. This is feasible since operators have access to official and standardised disassembly procedures, and handling precautions are shown based on the battery's configuration and condition. Economic benefits are also present in the form of reduced labour and diagnostic costs, as well as improved component recovery efficiency. Ultimately, this use case prevents damage to reusable modules and facilitates a higher degree of separation between recyclable parts and materials.

This use case addresses the complexity of disassembling battery packs. Ma et al. highlight the complexity due to the variety and intricate interconnections of components, making the process labour-intensive and energy-consuming. Moreover, they emphasise the contribution of this stage to the overall recycling process. [70]

The disassembly can be further eased through the implementation of automation and human-robot collaboration.

4.3.11. Eased Custom Compliance

There are significant obstacles to regulatory compliance, traceability, and safety when it comes to entering the European market because of the growing international commercialisation of batteries, especially from non-EU nations, where the regulations

mentioned above are not in place. The availability of data in the DPP can support the easing and standardisation of customs inspections, enabling a structured and automated assessment of regulatory compliance upon entry into European territory.

Without the DPP, customs officials must actually oversee a convoluted and frequently disjointed procedure to confirm that goods meet EU regulations. Delays in customs clearance, higher inspection and storage expenses, and the possible introduction of hazardous or non-compliant batteries into the market are the results of this. Additionally, the communication and effectiveness of the validation process are hindered by the absence of a common language among importers, authorities, and regulatory bodies.

When the DPP is available, however, all incoming batteries are accompanied by a complete and structured set of data that can be consulted by the competent authorities or by an automated DSS system responsible for checking compliance.

The diagram is observable in the Figure 4.24.

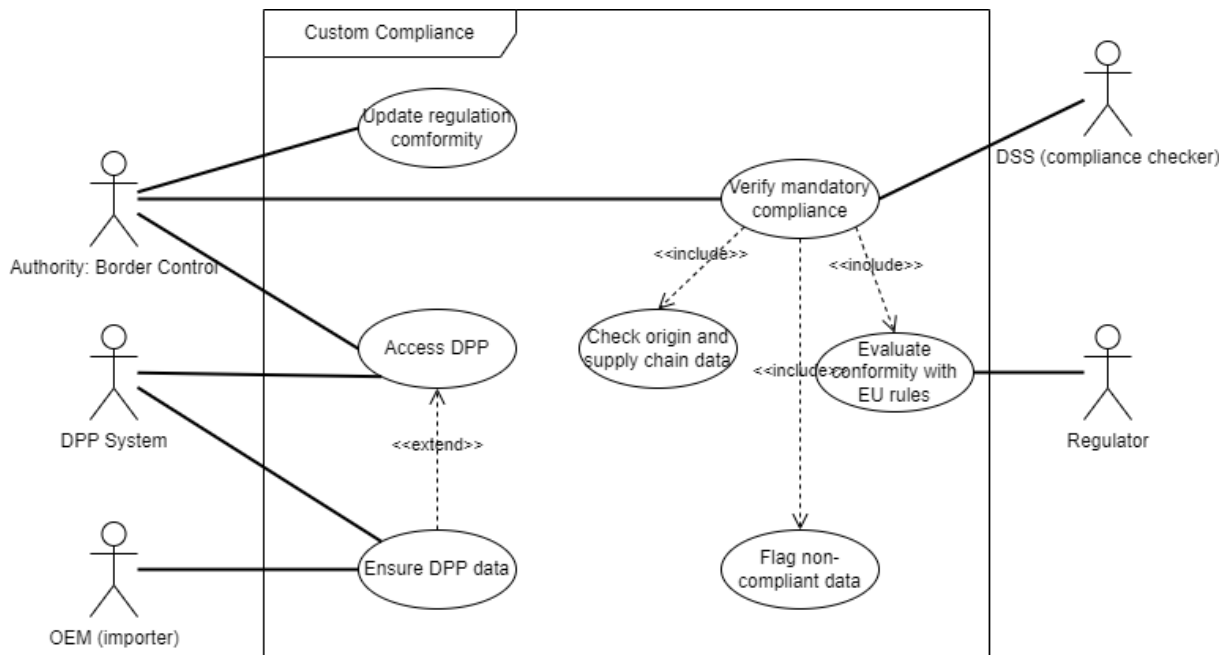


Figure 4.24: UML diagram - eased custom compliance

For the process to access critical data, verify compliance with EU regulations, and report any discrepancies, customs control is required. The system can stop harmful products from reaching end users by blocking the product's entry or initiating more thorough checks if non-compliance is discovered.

Product identifiers, material composition, carbon footprint data, compliance records, symbols, and technical data sheets are among the mandatory data that must be provided. Third-party certifications, ESG reports, importer traceability, and validation data are examples of optional data. The benefits are manifold, ranging from faster customs clearance and reduced storage and inspection costs to preventing the entry of

non-compliant or potentially hazardous batteries. In addition, the DPP promotes greater transparency, supports EU regulatory objectives, fosters a common language between authorities and economic operators, and aligns with global standards on product sustainability and safety.

5 Use Cases for Industrial Application

This section applies use cases to a real company active in the battery sector. The company's line analysis has been developed based on onsite visits and interviews, as well as materials provided by the company itself.

The use cases that align with the company's activities and context and provide a sufficient level of usefulness are further analysed to extract a practical, real-life application.

5.1. The Company: Envirobot España

Envirobot España is a company located in Madrid, specialised in the recycling of batteries declassified by manufacturers. Initially, the company focused on burying or incinerating batteries; however, with the rapid expansion of the battery market, it revised its business model to adopt an end-of-life battery management approach. The focus is now on recovering high-value raw materials and isolating metals that are harmful to the ecosystem.

The core process involves recycling alkaline and zinc-carbon batteries through hydrometallurgical treatments that convert waste into strategic metals, ensuring high recovery rates. The recycled batteries are mainly 18650 and EV batteries, while the remanufacturing phase is implemented only for 18650 models, represented in the Figure 5.1.

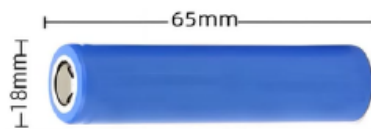


Figure 5.1: 18650 battery model

The decision to remanufacture 18650 batteries arises because the personnel noticed that they were often recycled (80% of the time) with SoH above 80%. They can be used in a wide range of devices due to their high energy density, long life cycles, wide availability, high discharge rates, and compact cylindrical size. As a result, this adaptability enables producers to create more portable, compact devices with longer battery life that are also more affordable over time.

Indeed, they are widely used in consumer electronic devices (laptops, power banks, and flashlights), EVs, including cars, bicycles, boats, electric scooters, and portable electronics (drones, gaming consoles, etc.).

The steps involved in the disposal and remanufacturing of discarded electromobility batteries are represented in the Figure 5.2 and further analysed.

The line is composed of six main phases.



Figure 5.2: Envirobat line

The first phase, battery receipt, is further subdivided into three steps, illustrated in Figure 5.3.

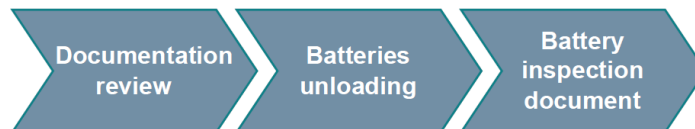


Figure 5.3: Battery reception

Upon arrival of the shipment, the logistic operator's documentation is reviewed and classified. Once the documentation has been verified, the battery packs and modules - mainly 18650 and EV batteries - are unloaded, and two samples from each batch are analysed. If the requirements are not satisfied, the entire batch is considered waste. During the reception, an inspection document is completed for each battery to ensure full traceability.

Once the first phase is completed, a review and characterisation of EOL batteries is performed to assess their condition, electrical performance, and external physical appearance. Indeed, batteries are characterised according to diverse parameters, such as voltage, capacity, model, battery manufacturer, origin, weight, and several others.

The remanufacturing process begins with disassembly, which is structured into two separate phases: unpacking for 18650 batteries and dismantling for EV batteries.

The unpacking process, represented in Figure 5.4, starts with the removal of the battery from the container, which is returned to the carrier.

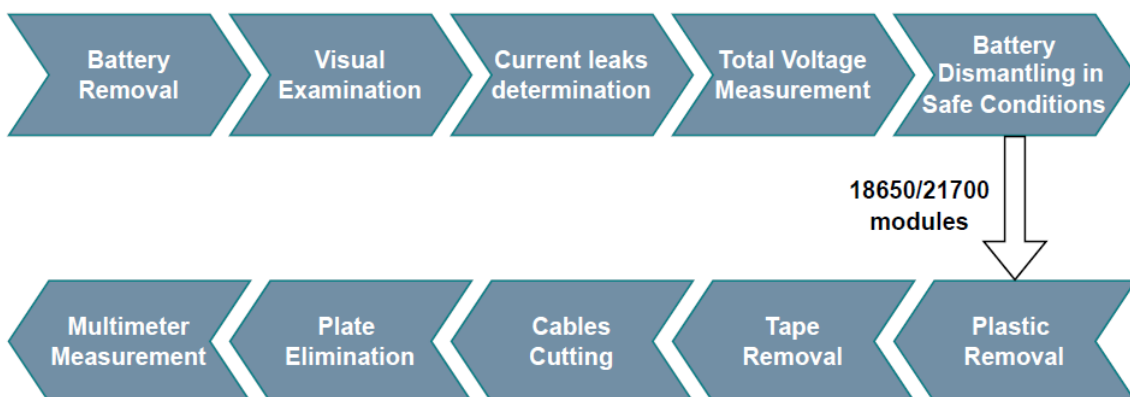


Figure 5.4: Disassembly – unpacking

The battery undergoes a visual examination to verify the absence of apparent signs of damage or deterioration on the exterior, such as cell swelling, leakage, or mechanical

deformation. At this point, the absence of current leaks between the two terminals and different parts of the casing is checked. After measuring the total voltage and verifying that the battery can be safely disassembled, the 18650 modules proceed to plastic casing removal to access the internal part of the battery; if present, the tape is also removed. Each cable connecting the cells to the BMS is cut individually to avoid short circuits, and the tin and nickel plate joining the cells is eliminated.

The output is the separation of individual cells, which are then measured to corroborate the minimum voltage. Cells above 2.5V continue the second-life process, while the others are recycled.

For the second disassembly phase (Figure 5.5), concerning EV batteries and 18650 batteries unsuitable for second life, it is fundamental that employees performing this process have proper training in high-voltage safety.

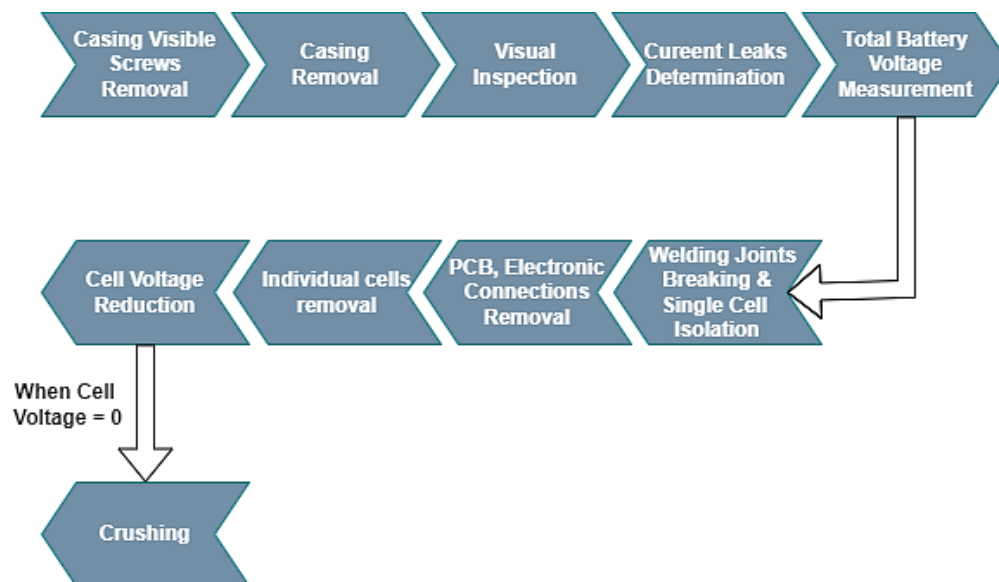


Figure 5.5: Disassembly – dismantling

The first step in the process is to remove the casing's easily accessible and visible screws. To avoid any possible safety concerns, a visual examination of the battery is necessary to find any indications of deterioration or damage. At this stage, a voltage measurement and leak check are performed.

Once the cell screws are visibly joined by welding, they are individually isolated, and the Printed Circuit Board (PCB) is removed together with electronic connections, plastics, and other high-voltage connection components.

Finally, the cells are immersed in a large bulk goods container filled with a saline water solution to produce a short circuit, reducing the cells' voltage to zero. The reduction of battery voltage is one of the most critical steps during the dismantling process in terms of safety.

The remanufacturing process continues with the technical testing phase (Figure 5.6).

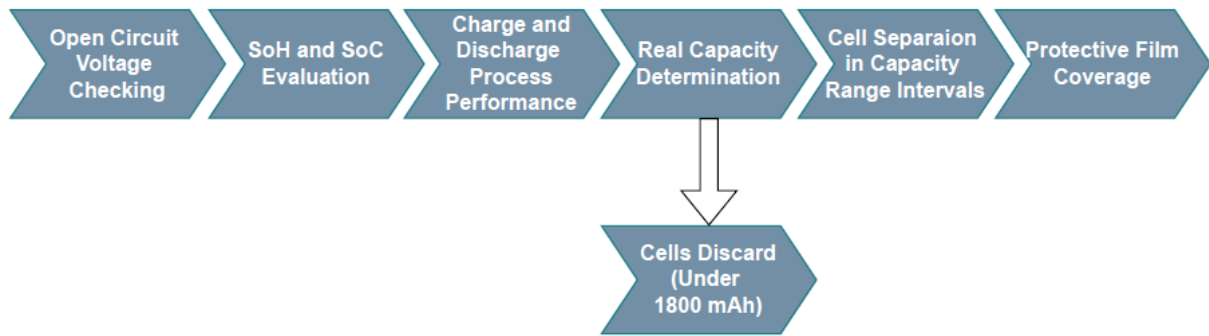


Figure 5.6: Technical testing

Starting with the Open Circuit Voltage (OCV) checking, if the value is normal, it is possible to proceed with testing the capacity, the internal Direct Current (DC) resistance to evaluate the SoH, and the State of Charge (SoC) balance between cells. The equipment performs a charge-discharge process between the maximum and minimum voltage ranges to determine the real capacity of each cell. Cells below 1800 mAh are discarded, while the others are clustered, based on their values in intervals of 100 mAh, so that they can be part of a battery pack of the same capacity range.

Finally, each group of cells with the same capacity range is inserted into the cell encapsulation equipment, where they are covered with protective film. At this point, the cells are suitable to be reused.

The last phase is the selection (Figure 5.7).

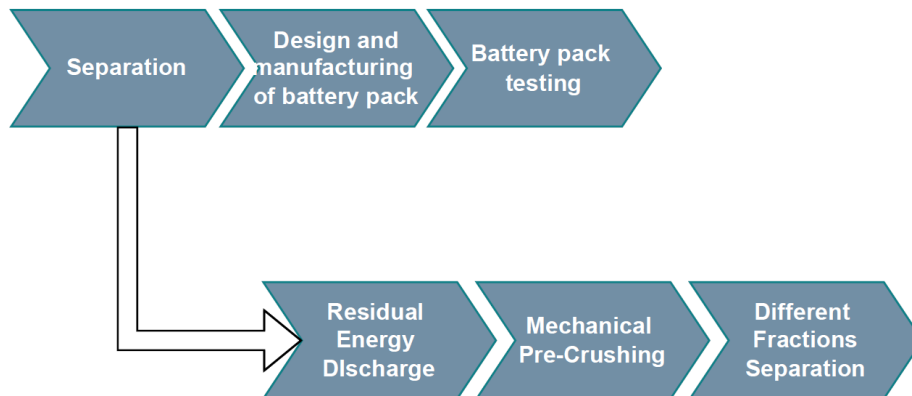


Figure 5.7: Selection

There is a separation between modules and cells, compliant or not, for second-life applications. Non-compliant elements are recycled, while the ones suitable for a second life are utilised in a new battery pack.

The process is concluded with the testing of the remanufactured battery pack.

The characterisation criteria to define suitable cells are the following:

- SoH is greater than or equal to 80% of its nominal capacity.
- The voltage of the cells constituting a module must be similar
- There should not be loss of tension over time.

- The internal resistance must be minimum.
- The physical appearance must be good.
- The electrical and electronic connections should be in perfect condition.

The designed and manufactured pack is characterised by a modular architecture, represented in the Figure 5.8, that can be customised and expanded to meet different energy requirements and needs. Additionally, it is easily maintained and repaired, ensuring long-term usability.

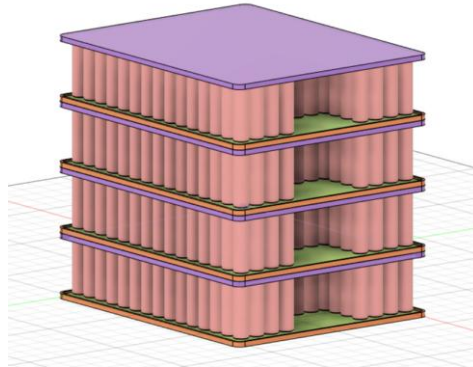


Figure 5.8: Envirobot - remanufactured battery pack

The battery packs find a wide variety of applications:

- Residential solar energy storage providing backup power and increasing self-consumption of solar-generated electricity,
- Off-grid and hybrid power systems to support homes, cabins, and remote locations where grid electricity is unavailable or unreliable.
- Uninterruptible Power Supply (UPS) that can ensure backup power for servers, data centres, hospitals, and telecommunication infrastructures.
- EV charging stations as an energy buffer to reduce peak demand from the grid.
- Portable and mobile power station in Recreational Vehicles (RVs), boats, and mobile command centres.
- RVs, campers, and off-grid camping

5.1.1. Relevant Use Cases Applicability and Benefits

Considering the company's line and the focus on remanufacturing activities, the use cases applicable to Envirobot are the ones referred to in that phase. In particular:

- Technical evaluation to define the most suitable second-life application
- Simplified residual value determination
- EV battery reuse in ESS
- Data aggregation from multiple DPPs
- Disassembly facilitation

The first four cases are applicable during the selection phase, particularly when designing and manufacturing new remanufactured battery packs and during their

testing. Instead, the disassembly facilitation can be implemented during the disassembly phases – unpacking and dismantling.

Additionally, the use case “Comprehensive battery risk assessment” is relevant along the whole line, given the high safety risk of post-use batteries.

The company’s responsible operators have identified the use case “simplified residual value determination” as the most useful one, given the high complexity in determining the value and the RUL of the remanufactured batteries containing several cells, all coming from different first-use batteries. In fact, by using the structured use case, the business can be certain of the projected battery's economic advantage and obtain an objective, standardised calculation of its monetary value. Enhancing client transparency and selecting the best second-life opportunity, while considering the variety of available applications and market channels, can aid in informed pricing decisions.

5.1.2. Gaps with the Identified Results and Criticalities

These use cases have great potential, but significant barriers exist to their actual implementation. Despite the organised line described in Chapter 5.1, Envirobat mainly relies on internal documentation and manual processes and does not currently have a fully digital traceability system. The systematic gathering, sharing, and reuse of data are hindered by unstructured and incompatible procedures, which reduce decision-making efficiency and increase operating expenses. The lack of standardised data flows also limits the ability to aggregate information from different sources, which is essential for supporting accurate technical assessments, value determination, and end-of-life integration.

The introduction of DPP-compatible use cases, combined with decision support systems, would enable Envirobat to move from a predominantly manual and fragmented process to a data-centric and standardised approach. Through trustworthy certification and assessment of remanufactured batteries, such a change could lower testing and processing expenses, improve safety and transparency, and open up new markets for used batteries. The current absence of traceability systems, inadequate digital integration, and the requirement for organisational and technical investments to support the methodical application of identified use cases are some of the structural obstacles that must be overcome in order to make this transition.

Moreover, the actual application of the described use cases was not possible due to a serious accident: several explosions ignited a fire that erupted for several days, causing the spread of a toxic smoke cloud across the area, given the hazardous substances and materials treated. The population in the surrounding municipalities, about 60,000 people, was forced to remain indoors until the emergency was over.

As cited in previous sections, the safety criticality is generally less addressed in circularity research [6]. The Envirobat accident is the final demonstration that implementing systems like the developed DSS is vital.

Chen et al. [6] identify six categories of safety risk sources during some EOL activities – collection, testing, sorting, discharge, disassembly, crushing, sieving, reassembly, and recycling (including hydrometallurgical, pyrometallurgical, and direct physical processes). These risk sources are technical – electronic, chemical, and mechanical – or non-technical – environmental, inter-organisational, and managerial.

All the mentioned activities were performed by Envirobat, representing the high-risk level the company was constantly exposed to. As represented in the Figure 5.9, all the activities should be controlled through safety regulations and standards that should be constantly updated by authorities and experts.

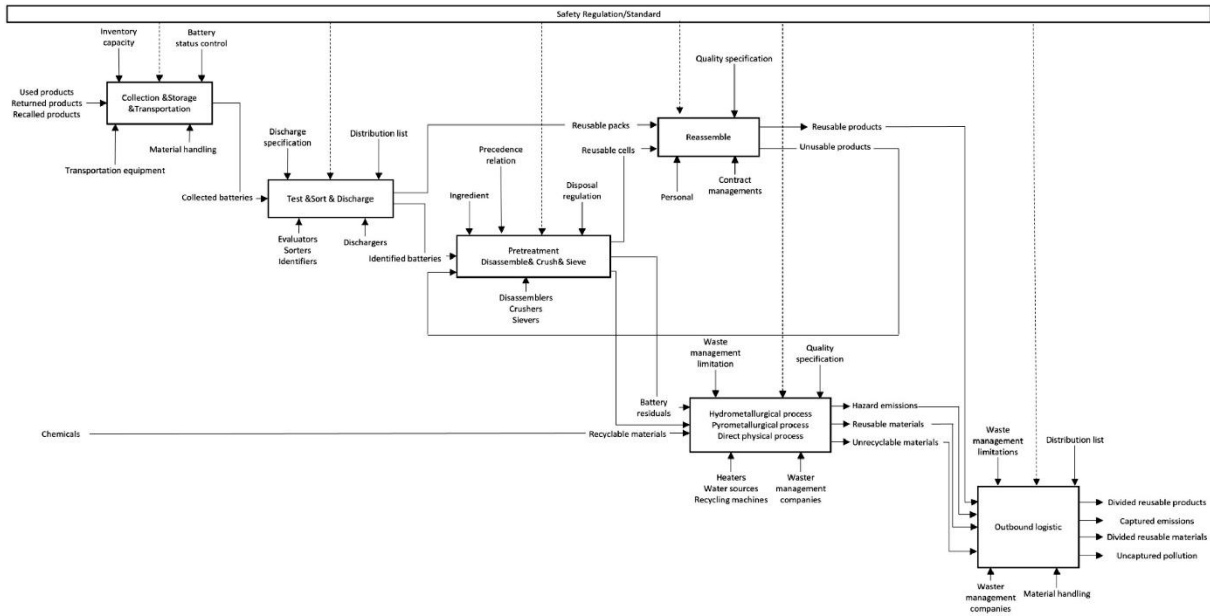


Figure 5.9: IDEF system for end-of-life management for lithium-ion batteries. [6]

Accidents of such magnitude might hinder the competitiveness and trustworthiness of second-life solutions in the EV battery context, posing an additional strict challenge to circularity and NZE goals.

Nevertheless, Envirobat is a company that prioritises safety, as evidenced by the documentation and authorisations they have. This is further representative of the imperative need for traceable and standardised information exchange among actors at a profound level of comprehension.

6 Discussion

Having presented the thesis results in detail and examined the industrial case, it is now essential to critically reflect on them and highlight the key findings along with their significance within the current academic context.

The developed value chain has been compared with the one identified by Wellten et al. [29] in their work published after this study. The result of their research derives from interviews conducted with experts in the sector of heavy-duty commercial vehicles, and it is observable in the Figure 6.1 .

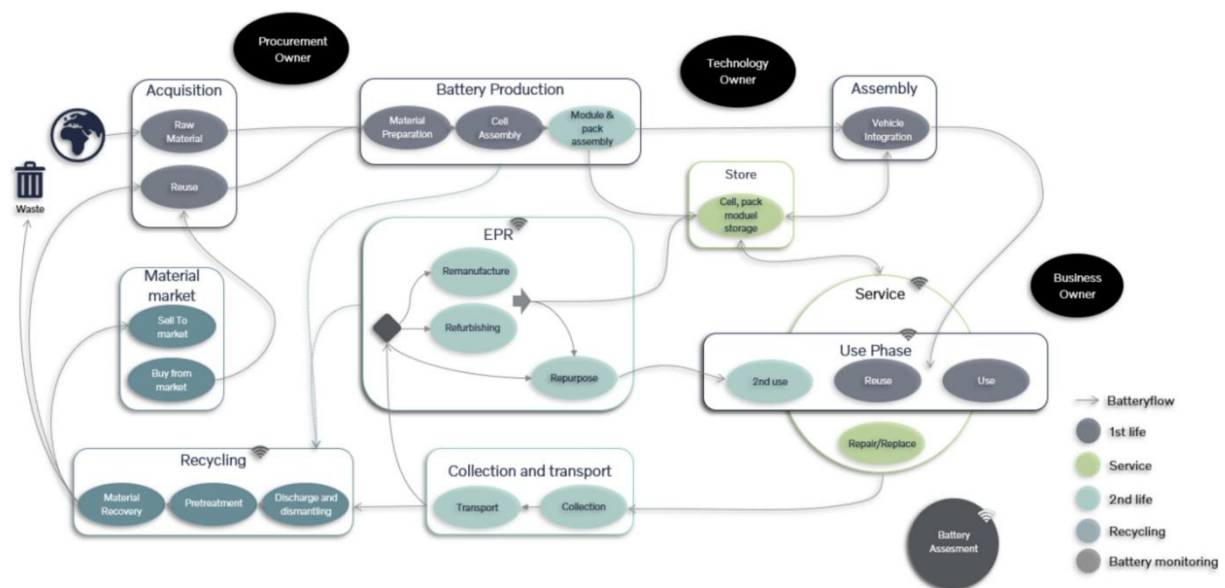


Figure 6.1: EV battery usage phase [29]

This comparison is interesting for validating the study conducted in this dissertation. Still, it is essential to take a reasonable distance, as it addresses the specific context of heavy-duty commercial EVBs, whereas this study generalises to the entire EV sector.

The phases identified by the authors correspond to the activities performed by the actors identified in this thesis. Indeed, in the mapping represented in the Figure 6.1, the ecosystem of different actors involved in EVBs is considered, ranging from raw material suppliers to EPR providers, customers, and recyclers.

Additionally, during the interviews, some critical issues related to information sharing emerged, including data granularity, ownership, transparency, and increased data collection, underscoring the importance of employing trusted data as paramount for ecosystem creation [29]. These aspects have been addressed and taken into consideration. Particularly, the information flows among the actors are enabled by DPP attributes that are, by definition, trustworthy and transparency-driven. Moreover, specific information and data preferences of various players are collected

in the cited paper [29] and categorised into seven groups: battery status information, product specifications, product location, complete history, sustainability and circularity, safety information, and actor-related information. It is easy to notice that they are all included in the DPP data attributes requirements, and, therefore, present in the information exchange of the developed value chain.

The discussion of these topics in the form of a peer review corroborates the significance and completeness of the value chain provided in this study. A distinctive contribution of this study is the holistic inclusion of all relevant stakeholders in the EV battery lifecycle. The developed value chain addresses the broader EV sector and includes actors that are frequently overlooked in previous models, such as collectors, diagnosers, and second-life OEMs, in contrast to works that concentrate on niche contexts, such as heavy-duty commercial vehicles, as provided in the article by Wellten et al. [29]. This ensures cross-sector applicability, qualifying the framework as a comprehensive operational tool for the entire industry.

Consequently, the value chain has proven to be not only a conceptual model but also an operational support in representing the actors, physical and information flows throughout the entire battery life cycle. It enables companies to precisely identify critical points and responsibilities associated with collecting the mandatory data required by regulations. This makes it possible, for example, to plan traceability activities, reducing compliance costs and the risks of inefficiency.

According to Zhu et al. [80] it is also a concept of fundamental importance, as it helps identify the actors with whom the company directly interacts, laying the groundwork for cooperation with the most pertinent supply chain partners. To facilitate the internal cycle strategies shown in the butterfly diagram (Figure 1.3), cooperation is necessary not only to enable second-life applications but also to incorporate circular economy strategies during the product's first life. Stakeholders should give Design for X strategies, specifically, Design for Disassembly, Remanufacturing, Reuse, and Recycling, priority in this situation. Furthermore, the establishment of a standardised modular design, supported and promoted by policymakers, would greatly facilitate second-life applications and reduce the amount of data needed to access and process the battery. The design aspect is consistent with other studies that highlight the importance of a common ground in manufacturing modularisation and standardisation [29], [82]. According to Nurdiawati et al. [24], traceability eases recalling the history of EV batteries, including various aspects, but it is not enough to compensate for the high variety of batteries; indeed, public authorities and regulatory bodies could incentivise standardisation through funds and regulations.

Additionally, the DPP-centric value chain (Chapter 4.1.2) is an addition to the CIRPASS work, and it highlights the need to consider the two products – the battery and the DPP - together since they evolve simultaneously. This aspect confirms the “digital twin” nature of the DPP often cited in the literature.

Mapping the battery value chain is therefore a fundamental prerequisite for understanding market dynamics, estimating the environmental and economic impacts of different technological and regulatory choices, and identifying areas where digital tools, such as DPP and DSS, can maximise benefits for all stakeholders.

Moving the focus to the Decision Support System, deploying a unified battery retirement pathway helps bridge gaps, creating a more cohesive and unified approach to battery lifecycle management and significantly enhancing the total economic and environmental benefits by simultaneously optimising multiparty interests [70]. The development of a pathway is addressed as a required future research by many authors. Ma et al. [70] state, "The integration of SoH estimation and remaining useful life (RUL) prediction into future pathway decisions should be studied and holds potential value."

The resultant DSS is aligned with the decision support framework developed by Zhuang et al. [83], mentioned in the Paragraph 2.2.1.2, which guides whether to reuse or recycle EOL batteries from EVs. Similarly, they are both dynamic in navigating the complex environment. They should be exploited as complementary tools to define a unified standard.

The Decision Support System has demonstrated clear practical value in standardising decisions relating to the end of battery life, one of the main barriers to the DPP, as reported by Psarommatis and May [53]. In the absence of structured tools, the choice between reuse, recycling or disposal is often based on manual assessments, with high margins of error and poor transparency, a future research topic suggested by Das [60]. The integration of the DSS with Digital Product Passport data, on the other hand, allows these processes to be automated and objectified, ensuring faster decisions based on shared criteria. From an industrial point of view, this translates into a reduction in the time spent on redundant diagnostics and greater reliability in the selection of second-life options. Additionally, the integration with the BMS allows the exploitation of dynamic data for decision-making, a fundamental aspect detected by Jensen et al. [49]. Moreover, the integration of the external database within the DSS enables external actors, such as insurance companies, energy market operators, policymakers, and others, to be part of the system and enhance information sharing through valuable data that is crucial for successful decision-making. This connection opens the possibility of expanding the scope of circular practices beyond the immediate value chain by providing independent verification, market integration, and additional services that reinforce trust and accountability.

Moreover, as previously stated, several authors disagree on the common decision of defining the second life based on a single performance threshold [15], [64], [91]. The DSS, with the support of the external database, enables actors to make more informed decisions, considering not only battery performance but also market demand and environmental factors, such as those obtainable through a battery charging station.

Additionally, the integration of charging stations can lower the end-users' "range anxiety," highlighted by Andrenacci et al. [25], through the representation of user-friendly guidelines and up-to-date data about the battery status and range.

Finally, the use cases not only exemplify how DPP data can be leveraged in practice but also provide insights for stakeholders across the value chain on how to maximise transparency, safety, and sustainability when managing end-of-life batteries. This is only possible if the existing information gap among stakeholders is reduced. The development of the information flow within the value chain should enable actors to identify and understand the data under their responsibility. However, policymakers and authorities should further act to simplify and incentivise the data supply process. Indeed, by integrating these tools, it is possible to reduce the burden on producers related to the additional sharing of information and intellectual property rights.

According to previous studies, it can also improve traceability, which is crucial for realising the circular economy. Traceability metrics along the value chain help identify extended use past the first life [50].

Use cases like thorough battery risk assessments show how access to DPP data can help prevent accidents during collection, transportation, and disassembly by giving stakeholders consistent safety guidelines and usage records. As the Envirobat case study illustrates, this can not only safeguard employees but also assist businesses in reducing civil liability and complying with transportation and environmental laws.

Moreover, use cases demonstrate how sustainability can be enhanced by extending product lifecycles, reducing the need for virgin materials, and minimising environmental impact. These examples also highlight novel business models that match financial incentives with the objectives of the circular economy by connecting technical viability to market opportunities. This aspect relates to a topic that often appears in literature: companies find circularity far from a financial advantage [29]; for instance, some of them find that repurposing requires more expenses than the actual battery price [4]. To this purpose, the DSS helps in conducting comprehensive life-cycle and cost-benefit analyses to evaluate the economic and environmental viability of different second-life use cases, a topic defined as crucial to overcome reuse challenges by Das [60]. Indeed, the use cases serve both as demonstrations of the DSS utility and as tools for its progressive adjustment, ensuring that the final system is coherent, operational, and aligned with industrial and regulatory realities.

The mapping of use cases to the real operational steps of Envirobat, including reception, characterisation, testing, and disassembly, illustrates the practical viability of the suggested system. This industry-based validation enhances the originality of the work by bridging the gap between academic models and practical implementation.

Considering recycling as the last possible opportunity, which is preferable to avoid, is a key aspect to support and highlight concerns about the regulations' uncertainties that

are leading, and if not well-addressed, will probably lead companies to prefer recycling over reuse [4], [48].

It is also necessary to address another matter in this context. The implementation of DSS and the proposed use cases can result in realistic scenarios only when sufficient volumes are available to achieve economies of scale, ensuring profitable and efficient processes. Stabilising supplier selection, lowering raw material price volatility, and acquiring materials necessary for production survival all depend on this requirement [29]. However, current batteries are frequently not made to be reused or repurposed, despite regulators, legislators, and environmental authorities adamantly advocating for circularity, a concept heavily emphasised in the literature and in previous paragraphs. Given that repurposed batteries must compete with new, purpose-built technologies, it is challenging to create a compelling high-volume business case due to the lack of volume, standards, and interoperability [71]. This issue might be further exacerbated by the financial incentive to prioritise recycling to meet the EU's content targets [4], [48], [71].

In contrast to existing literature that often focuses primarily on the battery pack as a single unit, the battery granularity at cell, module and pack levels is represented in this thesis, considering the importance of having data at all levels and the activities to be performed to ensure the maximisation of value retention of battery EOL resources. Granularity can be operationalised by translating high-level representations of the value chain into progressively more detailed layers of analysis. At the practical level, this means defining stakeholders not only as broad categories but as specific actors with explicit roles, responsibilities, and data interactions, as highlighted in the Chapter 4.1.2, referring to the DPP-centric value chain. Within the DSS, operational granularity is achieved by decomposing functions into sub-functions, which enables the tracing of inputs, controls, outputs, and mechanisms at different levels of abstraction. In the use cases, granularity is reflected in scenario-specific modelling, where general regulatory principles and DPP requirements are contextualised into concrete decision points.

This distinction enhances the technical robustness and practical applicability of the developed value chain by precisely identifying second-life opportunities, safety requirements, and residual value at a deeper level. This topic is significant because there is a lack of literature addressing the importance of representing the battery modular structure through lower granularity data levels in the DPP and the benefits for the circular economy. Only Pohlmann et al. [51] identified some attributes at the cell and module levels as necessary for EOL actors. Anyway, their relevance extends throughout the entire value chain, especially in second-life activities. It is relevant to highlight that some cells and modules' attributes are required in the DPP by regulations, but it has not been made clear how they can be represented in the battery passport.

In practice, granularity should be operationalised through a combination of standardisation and clearly defined processes. Standardised reporting templates and interoperable data formats can ensure that information provided by different actors follows a consistent level of detail, allowing data to be aggregated, compared, and integrated across the value chain. At the same time, process-driven requirements should specify what level of detail each actor must provide at different stages. In this way, granularity becomes not only a conceptual principle but a concrete practice.

Without the operationalisation of granularity, the Digital Product Passport risks remaining a superficial tool that provides only generic information. In such a scenario, its contribution to decision-making would be limited, and the benefits in terms of transparency, efficiency, and sustainability would be underachieved. Only by embedding granularity into practical reporting requirements and decision protocols the DPP can evolve from being a compliance-oriented repository of data into a transformative instrument that enables real circular economy practices.

In summary, in an environment in which the circular economy and a transition to electrical mobility are always more important, but, at the same time, hindered by several challenges (Chapter 1.2), the tools developed provide support in overcoming those barriers. The value chain offers a comprehensive overview of stakeholders, clarifying the flows of materials and information, and helping companies navigate institutional, supply chain, and firm-level barriers. The DPP addresses one of the most critical gaps identified in the literature: the lack of secure, standardised, and transparent data exchange. Enabling traceability helps meet regulatory goals for recycled content while lowering uncertainty in design, sourcing, and EOL management. This allows businesses to overcome internal challenges such as short-term financial reasoning, convert data into structured decisions, and guide recycling or second-life pathways in line with economic and environmental objectives. By offering ways to lower costs, improve interoperability, prolong product lifetimes, and increase resilience against supply chain disruptions, the suggested tools thus address both the systemic issues of the circular economy and the particular obstacles of the EV market. Together, they help ensure that industrial practices, societal expectations, and policy goals align, making the expansion of the EV industry a force for circularity rather than a hindrance. Moreover, they facilitate regulatory alignment, improve operational efficiency, and open up new market opportunities, thus helping to make the battery supply chain not only more sustainable but also more competitive, while attempting to establish a universally applicable standard to enhance second-life opportunities.

Overall, the thesis results develop a system that supports actors in transitioning to a circular economy, helping them lower costs, especially for new activities related to second-life, while considering environmental goals, with the final objective of unlocking second-life opportunities for EOL batteries.

6.1. Implications

In this section, the implications of the results are described for the different value chain actors and stakeholders interacting with the system. These implications should be intended as recommendations.

Indeed, the developed multidimensional approach, including technological innovation, aims to partially solve the DPP's barriers highlighted by Psarommatis and May [53], emphasising the need for stakeholder engagement and policy support.

All stakeholders should support the circular transition by contributing to data gathering in accordance with the required and voluntary guidelines. On the other hand, consortia should include stakeholders from all phases of the value chain to develop regulations and requirements that align with all actors and respect, at least partially, their interests.

Additionally, all actors should utilise the proposed use cases as insights into the possible benefits they could gain from the proposed DSS integrated with the DPP.

Raw Material Suppliers and Refiners

In an environment where recycling and reuse are becoming more and more important, maintaining high competitiveness requires rigorous cooperation with secondary markets. Suppliers cannot remain isolated from downstream actors as the demand for essential raw materials increases and regulatory frameworks require a greater proportion of recycled content. Collaboration and cooperation at this level of the value chain are crucial in the European context in the coming years, considering the absence of a strong raw material supply network. To decrease dependency on extra-EU countries, exploiting the secondary market is key.

The mapping and analysis of the value chain clarifies in detail which information on material composition, sourcing, and recycling efficiency must be collected and shared by the different actors. By making explicit the type and granularity of data required at each stage, it becomes possible to reduce regulatory uncertainty, align stakeholders with European requirements, and ensure consistent transparency throughout the entire chain.

Cell, Module and Pack Manufacturers

Batteries and their components are more likely to meet second-life criteria rather than being disposed of prematurely in recycling when DPP data is gathered and organised across various levels of granularity (cell, module, pack), as the suggested framework illustrates. The integration of DPP and DSS enables the standardisation of modular design processes and facilitates post-use diagnosis.

Additionally, manufacturers should adopt design-for-disassembly and design-for-reuse strategies, supported by granular data collection, to maximise the value

retention of their products. The implementation of these practices is particularly suitable for batteries, considering their modularity.

Finally, manufacturers might consider integrating their lines with disassembly and, more broadly, remanufacturing processes to leverage synergies and remain competitive in an increasingly circular economy. Such an integration, due to the complete knowledge of the assembly process, would further lower disassembly costs, opening up new automation possibilities, even if partial, in a highly manual activity.

OEMs

When DPP is combined with a decision support system, OEMs see a discernible reduction in compliance costs and legal risks. The framework demonstrates how OEMs can better manage warranty terms, traceability requirements, and second-life options by using standardised data flows. This is particularly crucial given the upcoming requirements of the EU Battery Regulation, which demand precise data collection and reporting.

In addition to complying with regulations, OEMs can use the DSS to enhance their business strategies. By moving from manual, disjointed evaluations to structured, data-driven choices, OEMs are better equipped to establish performance and safety thresholds for end-of-life and reuse. Furthermore, cooperation with second-life OEMs, made possible by open communication and synergies, shows promise as a business opportunity that will enable traditional manufacturers to remain competitive while entering new reuse and repurposing-related market segments.

To make collection and second-life purposes easier, OEMs should also think about acquisition strategies like ownership-based models (like leasing). Given that the OEM is typically the addressee of the EPR, this aspect is especially pertinent.

Collectors, Diagnosers, and Repairers

Collectors, diagnosers, and repairers frequently work in the most unpredictable stages of the battery lifecycle, when safety concerns, incomplete information and inconsistent procedures cause critical challenges. This research has significant consequences for these actors: access to structured DPP data can improve workplace safety, eliminate redundant testing, and reduce diagnostic time and costs.

Incorporating data into a DSS framework reduces margin of error and ensures transparency in the classification of EOL batteries through the standardisation of the decision-making process. Consequently, repairers can quickly and accurately identify batteries that require maintenance, while collectors and diagnosers lower the risks associated with handling, transportation, and non-compliance with regulations. Within this scope, investments in diagnostic tools, sensors, data analytics, and processing for collecting and verifying operational data are fundamental for effective monitoring and decision-making.

Second-Life OEMs and Remanufacturers

Second-life OEMs and remanufacturers stand to gain perhaps the most from the framework proposed in this thesis. The ability to access detailed technical and historical data through the DPP enables them to produce remanufactured batteries and storage systems with higher value, reliability, and market appeal. The use cases that have been developed allow new business models that were previously impeded by fragmented data. Remanufacturers can now balance economic viability and technical feasibility, which reduces the risks associated with investing in second-life applications. By bridging the gap between end-of-life management and the creation of renewed product value, this creates new revenue streams and reinforces their position as facilitators of circular economy strategies.

Recyclers

The study helps recyclers understand what data is needed to increase recycling efficiency and material recovery. Recyclers can streamline their operations, cut expenses, and guarantee adherence to more stringent environmental and safety regulations by having access to DPP data on composition and hazardous substances.

Additionally, they contribute to ecodesign improvements and the standardisation of modular architectures by providing feedback to upstream manufacturers. Indeed, recycling will become an integral part of a loop that maximises material recovery. Despite being considered in this thesis as the last available opportunity for EOL batteries, its importance persists nonetheless, for example, in the pre-use phases through proper recycling of scraps and the supply of recycled raw materials.

Policymakers and Public Authorities

A tangible basis for creating policies that go beyond general sustainability objectives and instead outline quantifiable specifications for data traceability and modular design is provided by the mapping of actors, flows, and responsibilities. Regulators can ensure greater levels of accountability and transparency while making compliance easier for businesses by encouraging the integration of DPP and DSS.

Additionally, the study provides strategic recommendations for future legislation, including supporting uniform second-life standards and offering incentives for modular and standardised battery design. Policymakers can create an environment where compliance is seen as a source of innovation and competitiveness rather than a burden by utilising the research's findings.

As widely discussed, this dissertation emphasises the importance of granularity in effectively representing the architecture modularity of the battery and increasing second-life possibilities. To proceed in this direction, it is fundamental that authorities, supported by industrial consortia, define the economic responsibility over cells and modules.

Finally, to make these tools actually useful and the battery ecosystem practical, issues related to actual regulations and standards must be addressed. First among them is the EU Battery Regulation's unrealistic recycling material targets, which would lead to premature recycling instead of closer R-strategies, or even without reaching the actual end-of-life. To move in this direction, incentives should be offered to companies to implement reuse and remanufacturing practices before recycling. Moreover, the ESPR target is in contradiction with the Circular Economy Action Plan, included in the EDG, which promotes repair over replacement, and consequently, over recycling, and more generally, with the ESPR.

Logistic Operators

Logistic operators play a crucial role in enabling the circular management of batteries, as they connect different actors across the value chain and ensure the safe and efficient movement of products between stages of the product lifecycle.

According to this study, the DPP and DSS's operations are directly impacted by their integration. First, they must handle batteries as hazardous materials, which necessitates specific packaging, storage, and transportation procedures that comply with safety and traceability regulations. Second, the adoption of the DPP provides an opportunity to enhance logistics efficiency: standardised data on battery state of health, composition, and history allows operators to plan shipments more accurately, optimise load consolidation, and reduce unnecessary handling. Third, reverse logistics becomes a central component of their operations, as end-of-life and post-use batteries must be collected, sorted, and redirected to appropriate destinations based on DSS recommendations.

Additionally, logistic operators are expected to act as active data contributors to the DPP by recording transfer points, handling conditions, and incidents during transportation.

Ultimately, a robust collaboration with OEMs is essential to the successful implementation of collection strategies.

7 Conclusion

The purpose of this thesis was to investigate how the integration of the Digital Product Passport into a Decision Support System can support the transition towards a circular economy for electric vehicle batteries. The study's goals were to develop a thorough value chain that includes both physical and informational flows, determine beneficial uses for DPP data, and suggest a framework for making decisions that lessen uncertainty in second-life evaluations.

To achieve these objectives, the thesis combined a review of the existing academic and regulatory landscape with the development of original models. First, to map stakeholders, activities, and data requirements at the three granular levels (pack, module, and cell), a comprehensive and multi-stakeholder value chain of EV batteries was created. Additionally, an integration with a DPP-centric value chain has been relevant for individualising stakeholders' roles in creating the battery passport. The following step was to design the DSS using the IDEF0 methodology, which formalised the decision-making process of EOL batteries by combining, from an information perspective, inputs (data from the DPP, BMS, and external database), outputs (second-life option and updated DPP), controls (regulations, standards and external factors), and resources (testing tools and expertise), relative to the battery under process. The integration of an external database allows the interaction of actors outside the battery value chain, creating a wide and comprehensive ecosystem based on information exchange. Lastly, practical use cases along the value chain were mapped, and the Envirobat industrial case was used to validate the framework's applicability by comparing the suggested use cases with actual operational procedures.

The general objectives and requirements outlined by existing and upcoming regulations were taken into consideration when taking all of these actions. The fundamental goal was to anticipate the practical effects of the legal framework and ensure compliance with it by creating instruments that can actively assist stakeholders during the last stage of implementation. In this way, the suggested models and methodologies are indeed to function as operational guidelines that can convert regulatory ambition into practical practices, rather than maintaining an abstract academic structure. As a result, the study helps close the gap between industrial realities and policy goals in the circular economy by providing a set of tools that can ease compliance, lower uncertainty, and promote a more seamless transition to the successful opening of new and more second-life opportunities, but also by highlighting main barriers hindering the potential benefits of the DPP, such as the granularity issue.

In conclusion, this thesis's primary contribution is the creation of an operational and integrated framework that converts the Digital Product Passport's regulatory requirements into useful industry tools. In contrast to previous research, which frequently discusses market, technological, or regulatory issues separately, this work suggests a comprehensive strategy.

7.1. Limitations and Future Development

This thesis provides a comprehensive framework for managing and optimising battery end-of-life, exploiting the DPP under the current European regulatory framework. However, further improvements and future research opportunities may emerge to strengthen the validation of results and deepen the understanding of the context.

Recommendations for future development are the following:

- Verifying the value chain information flow: The current analysis defined the proposed data based on DPP requirements and stakeholders' activities and validated the results through a peer review. Future research and interviews might verify the alignment with each stakeholder and their ability to compute and supply those values.
- Integrating the DSS with computing algorithms and testing it on a real case: The developed DSS should be integrated with algorithms to compute performance indicators, such as SoH and RUL, and residual value and to compare it with market data to ensure an economically and environmentally competitive second-life alternative. Additionally, the system should be tested on real cases to validate its functionality.
- Providing a quantitative modelling of costs, environmental and social impacts: The benefits of the developed use cases are evaluated with strong qualitative insights, but a comprehensive cost-benefit analysis supported by empirical data would strengthen the conclusions.
- Further investigating relationships and contractual agreements with and between post-use actors: Exploiting relationships and contracts between actors in the pre-use and post-use phases can offer insights about collaboration and opportunities for strengthening cooperation. Indeed, it would be possible to recognise synergies and incentivise circular economy strategies in both pre- and post-use activities.
- Extending the study to extra-EU: The value chain was created solely with the EU context in consideration, based on European regulatory frameworks and DPP requirements. However, because of the scarcity of raw materials, many actors, particularly in the extraction phase, are scarce in Europe. To achieve climate and environmental goals, the model should be validated and integrated globally, considering national regulatory frameworks as well as potential alignments and collaborative opportunities.

- Further investigate safety along the whole value chain: To avoid accidents like Envirobat España, a complete analysis of possible risks and safety issues along the value chain should be in-depth evaluated, introducing further guidelines and stricter regulations in the battery treatment and transportation, given the high content of hazardous and toxic material.
- Studying under-researched topics: The objectives of this dissertation were defined because of the existing literature gaps. However, two specific issues — data granularity and the connection between DPP roles and value chain stakeholders — do not appear to have been addressed in any research or literature, despite their high relevance in view of the 2027 DPP implementation deadline. It is indeed fundamental to further investigate these topics to ensure a smooth and timely transition to the circular economy within the next two years.
- Actual DPP second-life opportunities: Once the DPP is implemented, it will be fundamental to evaluate actual second-life opportunities that can be derived from its integration with Decision Support Systems and other supporting tools and standards, and identify the gaps with forecasted implementations.
- Defining clearly the DPP deactivation scenario: In the current regulatory framework, the DPP must be deactivated when the product is no longer available and its components are reutilised, as specified in the Chapter 4.1.2. Anyway, as represented through the use case 6, multiple DPPs of diverse components are helpful to create the DPP of the new remanufactured product. Based on this aspect, the deactivation scenario should be thoroughly analysed and defined, at least until the battery modularity is represented in the DPP, as this aspect would facilitate this use case.

Acknowledging both the complexities and the opportunities that will characterise the coming years in the field of circularity, and, more broadly, in sustainability, it becomes crucial to critically reflect on the actual impact of the Digital Product Passport. From the perspective of policymakers and public authorities, the key question is not only how to ensure a timely implementation, but whether such an instrument will concretely drive measurable improvements in the circular economy. Considering that full enforcement is expected in less than two years, there is an urgent need to assess the readiness of industry stakeholders, the maturity of supporting infrastructures, the coherence of regulatory frameworks, and the actual feasibility of a circular transition. Only by addressing these aspects will it be possible to transform the DPP from a regulatory requirement into an incentive for transition, capable of fostering transparency, resource efficiency, and sustainable value creation across the entire battery value chain.

“Moving towards a truly circular economy will not be achieved in one step” [3]. As this dissertation demonstrates, with sustained progress, continuous innovation,

collaborative effort, and intense societal commitment, circularity can be transformed, step by step, from a distant aspiration into a tangible reality.

Bibliography

- [1] Circle Economy Foundation, "The circularity gap report," 2024.
- [2] European Council, "European Green Deal," European Council, 2019. [Online]. Available: <https://www.consilium.europa.eu/en/policies/european-green-deal/>. [Accessed 10 July 2025].
- [3] Ellen MacArthur Foundation, "Growth within: A circular economy vision for a competitive Europe," 2015.
- [4] Y.-C. Lin, Y. Bekele Beyene and L. Bertling Tjernberg, "Implications of EU Battery Regulation on Circular Economy: Barriers and Opportunities for Repurposing Electric Vehicle Batteries," in *2024 IEEE PES Innovative Smart Grid Technologies Europe (ISGT EUROPE 2024)*, 2024, doi: 10.1109/ISGTEUROPE62998.2024.10863545
- [5] European Commission, "Towards a circular economy: A zero waste programme for Europe," Brussels, 2014.
- [6] Z. Chen, A. Yildizbasi, Y. Wang and J. Sarkis, "Safety in lithium-ion battery circularity activities: A framework and evaluation methodology," *Resources, Conservation & Recycling*, vol. 193, 2023, doi: 10.1016/j.resconrec.2023.106962
- [7] J. Potting, M. Hekkert, E. Worrell and A. Hanemaaijer, *Circular Economy: Measuring innovation in the product chain*, PBL Netherlands Assessment Agency, 2017.
- [8] J. Kirchherr, D. Reike and M. Hekkert, "Conceptualizing the circular economy: An analysis of 114 definitions," *Resources, Conservation & Recycling*, vol. 127, pp. 221-232, 2017, doi: 10.2139/ssrn.3037579
- [9] S. Franco and I. Giannoccaro, "Dynamic Capabilities and Microfoundations to Overcome Barriers to Circular Economy Implementation," *Business Strategy and the Environment*, vol. 34, no. 4, pp. 4392-4408, 2025, doi: 10.1002/bse.4171

- [10] M. Hina, C. Chauhan, P. Kaur, S. Kraus and A. Dhir, "Drivers and barriers of circular economy business models: Where we are now, and where we are heading," *Journal of Cleaner Production*, vol. 333, p. 130049, 2022, doi: 10.1016/j.jclepro.2021.130049
- [11] P. Centobelli, R. Cerchione, D. Chiaroni, P. Del Vecchio and A. Urbinati, "Designing business models in circular economy: A systematic literature review and research agenda," *Business Strategy and the Environment*, vol. 29, no. 4, pp. 1734-1749, 2020, doi: 10.1002/bse.2466
- [12] M. K. Nallapaneni and S. S. Chopra, "Leveraging Blockchain and Smart Contract Technologies to Overcome Circular Economy Implementation Challenges," *Sustainability*, vol. 14, no. 15, 2022, doi: 10.3390/su14159492
- [13] S. Lawrenz, M. Nippraschk, P. Wallat, A. Rausch, D. Goldmann and A. Lohrengel, "Is it all about Information? The Role of the Information Gap between Stakeholders in the Context of the Circular Economy," in *28th CIRP Conference on Life Cycle Engineering*, 2021, doi: 10.1016/j.procir.2021.01.118
- [14] R. H. Reich, J. Ayan, L. Alaerts and K. Van Acker, "Defining the goals of Product Passports by circular product strategies," in *30th CIRP Life Cycle Engineering Conference*, 2023, doi: 10.1016/j.procir.2023.02.044
- [15] M. Hassini, E. Redondo-Iglesias and P. Venet, "Second-Life Batteries Modeling for Performance Tracking in a Mobile Charging Station," *World Electric Vehicle Journal*, vol. 14, no. 4, 2023, doi: 10.3390/wevj14040094
- [16] European Union, "Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries (Text with EEA relevance)," Brussels, 2023.
- [17] IEA, "Global EV Outlook," IEA, 2025.
- [18] IEA, "Transport," 2023. [Online]. Available: <https://www.iea.org/energy-system/transport#tracking>. [Accessed 21 July 2025].
- [19] E. Kristiningrum, R. Nurcahyo, S. Sumaedi, F. Dwitawiyarti and M. Asvial, "A Sustainable Approach to Energy Management: Multisectoral Collaboration for Second-Life Electric Vehicle Batteries," in *2025 2nd International Conference on Advanced Innovations in Smart Cities (ICAISC)*, Jeddah, Saudi Arabia, 2025, doi: 10.1109/ICAISC64594.2025.10959600

- [20] Motus-E; Strategy&; Politecnico di Milano, "Electric vehicle battery recycling @2050: evolutionary scenarios and enabling technologies," 2023.
- [21] N. Jiao and S. Evans, "Business models for sustainability: the case of second-life electric vehicle batteries," *Procedia CIRP*, vol. 40, pp. 250-255, 2016, doi: 10.1016/j.procir.2016.01.114
- [22] X. Sun, H. Hao, P. Hartmann, Z. Liu and F. Zhao, "Supply risks of lithium-ion battery materials: An entire supply chain estimation," *Materials Today Energy*, vol. 14, p. 100347, 2019, doi: 10.1016/j.mtener.2019.100347
- [23] IEA, "Critical Minerals Data Explorer," IEA, 21 May 2025. [Online]. Available: <https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer>. [Accessed 29 August 2025].
- [24] A. Nurdiawati and T. K. Agrawal, "Creating a circular EV battery value chain: End-of-life strategies and future perspective," *Resources, Conservation & Recycling*, vol. 185, 2022, doi: 10.1016/j.resconrec.2022.106484
- [25] N. Andrenacci, F. Vitiello, C. Boccaletti and F. Vellucci, "Powering the Future Smart Mobility: A European Perspective on Battery Storage," *Batteries*, vol. 11, no. 185, 2025, doi: 10.3390/batteries11050185
- [26] IEA, "EV Battery Supply Chain Sustainability," IEA, Paris, 2024.
- [27] A. Zahoor, R. Kun, G. Mao, F. Farkas, A. Sapi and Z. Konya, "Urgent needs for second life using and recycling design of wasted electric vehicles (EVs) lithium-ion battery: a scientometric analysis," *Environmental Science and Pollution Research*, vol. 31, pp. 43152-43173, 2024, doi: 10.1007/s11356-024-33979-3
- [28] Y. Kotak, C. Marchante Fernandez, L. Canals Casals, B. Satishbhai Kotak, D. Koch, C. Geisbauer, L. Trilla, A. Gomez-Nunez and H.-G. Schweiger, "End of Electric Vehicle Batteries: Reuse vs. Recycle," *Energies*, vol. 14, p. 2217, 2021, doi: 10.3390/en14082217
- [29] J. Wellten, J. Angleis and E. Ribeiro da Silva, "Enabling a viable circular ecosystem for electric vehicle batteries," *Technological Forecasting & Social Change*, vol. 210, p. 123976, 2025, doi: 10.1016/j.techfore.2024.123876
- [30] T. Wautelet and A.-C. Ayed, "D2.2 Exploring possible Digital Product Passport (DPP) use cases in battery, electronics and textile value chains," CIRPASS, 2024.

- [31] DUKOSI, "Battery State of Health (SoH): The Powerhouse Behind the Battery Passport," 10 September 2024. [Online]. Available: <https://www.dukosi.com/blog/battery-state-of-health-soh-the-powerhouse-behind-the-battery-passport>. [Accessed 29 August 2025].
- [32] L. H. Guenther, V. Klein, G. Loef, A. Pohl, H. Okube, R. Winterbur, G. Röwer, B. Wegener, R. Goertz and S. Bracke, "Second Life for Lithium-Ion Traction Batteries," *Sustainability*, vol. 16, no. 17, 2024, doi: 10.3390/su16177288
- [33] European Commission, "Sustainable Products Initiative," [Online]. Available: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12567-Sustainable-products-initiative_en. [Accessed 27 July 2025].
- [34] Battery Pass Consortium, "Battery Passport Content Guidance: Achieving compliance with the EU Battery Regulation and increasing sustainability and circularity," 2023.
- [35] C. A. Rufino Junior, E. Riva Sanseverino, P. Gallo, D. Koch, D. Sergej, G. Walter, L. Trilla, V. J. Ferreira, G. Benveniste Pérez, Y. Kotak, J. Eichman, H.-G. Schweiger and H. Zanin, "Towards to Battery Digital Passport: Reviewing Regulations and Standards for Second-Life Batteries," *Batteries*, vol. 10, no. 115, 2024, doi: 10.3390/batteries10040115
- [36] OECD, "Extended Producer Responsibility: Basic facts and key principles," OECD Publishing, Paris, 2024.
- [37] P. K. Mallick, K. B. Salling, D. C. Pigosso and T. C. McAloone, "Designing and operationalising extended producer responsibility under the EU Green Deal," *Environmental Challenges*, vol. 16, 2024, doi: 10.1016/j.envc.2024.100977
- [38] Y. Gupt and S. Sahay, "Review of extended producer responsibility: A case study approach," *Waste Management & Research*, vol. 33, no. 7, pp. 596-611, 2015, doi: 10.1177/0734242X15592275
- [39] H. da Silva Hyldmo, S. Angen Rye and D. Vela-Almeida, "A globally just and inclusive transition? Questioning policy representations of the European Green Deal," *Global Environmental Change*, vol. 89, 2024, doi: 10.1016/j.gloenvcha.2024.102946
- [40] J. Hereu-Morales, A. Segarra and C. Valderrama, "The European (Green?) Deal: a systematic analysis of environmental sustainability," *Sustainable Development*, vol. 32, no. 1, pp. 647-661, 2023, doi: 10.1002/sd.2671

- [41] European Council, "Circular Economy," 2024. [Online]. [Accessed 10 July 2025].
- [42] European Commission, "End-of-Life Vehicles," 2023. [Online]. Available: https://environment.ec.europa.eu/topics/waste-and-recycling/end-life-vehicles_en. [Accessed 31 August 2025].
- [43] World Economic Forum; RMI; Global Battery Alliance, "Powering the Future: Unlocking Energy Storage for Net Zero," World Economic Forum, 2025.
- [44] European Commission, "Ecodesign for Sustainable Products Regulation," 2024. [Online]. Available: https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/ecodesign-sustainable-products-regulation_en. [Accessed 10 July 2025].
- [45] E. Blot, "External impacts of new EU sustainable product standards," 15 April 2025. [Online]. Available: <https://ieep.eu/publications/external-impacts-of-new-eu-sustainable-product-standards/>. [Accessed 30 August 2025].
- [46] A. M. Bundgaard, R. D. Huulgaard and A. Remmen, "Getting the priorities right in material efficiency: from the Ecodesign Directive to the Ecodesign for Sustainable Products Regulation," in *2024 Electronic Goes Green 2024+ (EGG)*, Berlin, 2024, doi: 10.23919/EGG62010.2024.10631182
- [47] Council of the EU, "Council adopts new regulation on batteries and waste batteries," 10 July 2023. [Online]. Available: <https://www.consilium.europa.eu/en/press/press-releases/2023/07/10/council-adopts-new-regulation-on-batteries-and-waste-batteries/>. [Accessed 13 July 2025].
- [48] C. Altuntas Vural, P. van Loon, Á. Halldórsson, J. Fransson and F. Josefsson, "Life after use: circular supply chains for second-life of electric vehicle batteries," *Production Planning & Control*, vol. 36, no. 9, pp. 1229-1246, 2025, doi: 10.1080/09537287.2024.2353379
- [49] S. F. Jensen, J. H. Kristensen, S. Adamsen, A. Christensen and B. V. Waehrens, "Digital product passports for a circular economy: Data needs for product life cycle decision-making," *Sustainable Production and Consumption*, vol. 37, 2023, doi: 10.1016/j.spc.2023.02.021
- [50] T. K. Agrawal, J. Angelis, J. R. Thakur, M. Wiktorsson and R. Kalaiarasan, "Enabling circularity of electric vehicle batteries - the need for appropriate

- traceability,” in *IEEE International Conference on Technology Management, Operations and Decisions (ICTMOD)*, Marrakech, 2021, doi: 10.1109/ICTMOD52902.2021.9739531
- [51] A. Pohlmann, M. Popowics, J.-P. Schöggel and R. J. Baumgartner, “Digital product passports for electric vehicle batteries: Stakeholder requirements for sustainability and circularity,” *Cleaner Production Letters*, vol. 8, 2025, doi: 10.1016/j.clpl.2024.100090
- [52] CIRPASS Consortium, “D3.2 DPP System Architecture (Version 1.9),” 2023.
- [53] F. Psarommatis and G. May, “Digital Product Passport: A Pathway to Circularity and Sustainability in Modern Manufacturing,” *Sustainability*, vol. 16, no. 1, 2024, doi: 10.3390/su16010396
- [54] Battery Pass, “Unlocking the Value of the EU Battery Passport,” 2024.
- [55] DIN; DKE, “Requirements for data attributes of the battery passport,” 2025.
- [56] K. Berger, J.-P. Schöggel and R. J. Baumgartner, “Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases,” *Journal of Cleaner Production*, vol. 353, 2022, doi: 10.1016/j.jclepro.2022.131492
- [57] L. Stratmann, G. Hoeborn, C. Pahl and G. Schuh, “Classification of Product Data for a Digital Product Passport in the Manufacturing Industry,” in *Conference on Production Systems and Logistics (CPSL)*, 2023, doi: 10.15488/13463
- [58] Battery Pass, “Battery Passport Data Attribute Longlist,” 2025.
- [59] M. Philippot, D. Costa, M. S. Hosen, A. Senécat, E. Brouwers, E. Nanini-Maury, J. Van Mierlo and M. Messagie, “Environmental impact of the second life of an automotive battery: Reuse and repurpose based on ageing tests,” *Journal of Cleaner Production*, vol. 366, p. 132872, 2022, doi: 10.1016/j.jclepro.2022.132872
- [60] K. P. Das, “A Perspective on the Challenges and Prospects of Realizing the Second Life of Retired EV Batteries,” *Batteries*, vol. 11, no. 5, 2025, doi: 10.3390/batteries11050176
- [61] K. Richa, C. Babbitt, N. Nenadic and G. Gaustad, “Environmental trade-offs across cascading lithium-ion battery life cycles,” *The International Journal of Life Cycle Assessment*, vol. 22, no. 1, 2015, doi: 10.1007/s11367-015-0942-3

- [62] N. Jiao and S. Evans, "Secondary use of Electric Vehicle Batteries and Potential Impacts on Business Models," *Journal of Industrial and Production Engineering*, vol. 33, pp. 348-354, 2016, doi: 10.1080/21681015.2016.1172125
- [63] J. Zhu, I. Mathews, D. Ren, W. Li, D. Cogswell, B. Xing, T. Sedlatschek, S. N. R. Kantareddy, M. Yi, T. Gao, Y. Xia, Q. Zhou, T. Wierzbicki and M. Z. Bazant, "End-of-life or second-life options for retired electric vehicle batteries," *Cell Reports Physical Science*, vol. 2, no. 8, 2021.
- [64] M. Etxandi-Santolaya, L. Canals Casals, T. Montes and C. Corchero, "Are electric vehicle batteries being underused? A review of current practices and sources of circularity," *Journal of Environmental Management*, vol. 338, 2023, doi: 10.1016/j.jenvman.2023.117814
- [65] J. Li, S. He, Q. Yang, Z. Wei, Y. Li and H. He, "A Comprehensive Review of Second Life Batteries Toward Sustainable Mechanisms: Potential, Challenges, and Future Prospects," *IEEE TRANSACTIONS ON TRANSPORTATION ELECTRIFICATION*, vol. 9, no. 4, pp. 4824 - 4845, 2023, doi: 10.1109/TTE.2022.3220411
- [66] A. Spindlegger, L. Slotyuk, A. Jandric, R. G. De Souza, S. Prenner and F. Part, "Environmental performance of second-life lithium-ion batteries repurposed from electric vehicles for household storage systems," *Sustainable Production and Consumption*, vol. 54, pp. 227-240, 2025, doi: 10.1016/j.spc.2025.01.003
- [67] A. I. López, A. Ramírez-Díaz, I. Castilla-Rodríguez, J. Gurriarán and J. A. Mendez-Perez, "Wind farm energy surplus storage solution with second-life vehicle batteries in isolated grids," *Energy Policy*, vol. 173, p. 113373, 2023, doi: 10.1016/j.enpol.2022.113373
- [68] L. Canals Casals and B. Amante García, "Second-Life Batteries on a Gas Turbine Power Plant to Provide Area Regulation Services," *Batteries*, vol. 3, no. 1, 2017, doi: 10.3390/batteries3010010
- [69] J. Lacap, J. W. Park and L. Beslow, "Development and Demonstration of Microgrid System Utilizing Second-Life Electric Vehicle Batteries," *Journal of Energy Storage*, vol. 41, p. 102837, 2021, doi: 10.1016/j.est.2021.102837
- [70] R. Ma, S. Tao, X. Sun, Y. Ren, S. Chongbo, G. Ji, J. Xu, X. Wang, X. Zhang, Q. Wu and G. Zhou, "Pathway decisions for reuse and recycling of retired lithium-ion batteries considering economic and environmental functions," *Nature Communications*, vol. 15, 2024, doi: 10.1038/s41467-024-52030-0

- [71] W. Bernhart, H. Kaur, T. Hotz and S. Koper, "Second life and recycling: Enabling a circular battery economy," 20 June 2023. [Online]. Available: <https://www.rolandberger.com/en/Insights/Publications/Second-life-and-recycling-Enabling-a-circular-battery-economy.html>. [Accessed 5 August 2025].
- [72] X. Gu, H. Bai, X. Cui, J. Zhu, W. Zhuang, Z. Li, X. Hu and Z. Song, "Challenges and opportunities for second-life batteries: Key technologies and economy," *Renewable and Sustainable Energy Reviews*, vol. 192, 2004, doi: 10.1016/j.rser.2023.114191
- [73] E. Braco, I. San Martín, A. Berrueta, P. Sanchis and A. Ursúa, "Experimental assessment of cycling ageing of lithium-ion second-life batteries from electric vehicles," *Journal of Energy Storage*, vol. 32, 2020, doi: 10.1016/j.est.2020.101695
- [74] L. Canals Casals, B. Amante García and C. Canal, "Second life batteries lifespan: Rest of useful life and environmental analysis," *Journal of Environmental Management*, vol. 232, pp. 354-363, 2019, doi: 10.1016/j.jenvman.2018.11.046
- [75] M. Alizadeh Afroozi, M. Gramifar, B. Hazratifar and M. M. Keshvari, "Optimization of Lithium-Ion Battery Circular Economy in Electric Vehicles in Sustainable Supply Chain," *Battery Energy*, 2024, doi: 10.1002/bte2.20240057
- [76] M. E. Porter, "Competitive strategy: Techniques for analyzing industries and competitors," vol. 1, no. 2, pp. 12-17, 1997.
- [77] D. Simchi-Levi, P. Kaminsky and E. Simchi-Levi, "Designing and Managing the Supply Chain: Concepts, Strategies, and Case Studies," *Journal of Business Logistics*, vol. 22, no. 1, pp. 259-261, 2001, doi: 10.1002/j.2158-1592.2001.tb00165.x
- [78] C. Prahinski and C. Kocabasoglu, "Empirical research opportunities in reverse supply chains," *Omega*, vol. 34, pp. 519-532, 2006, doi: 10.1016/j.omega.2005.01.003
- [79] C. Nuss, R. Sahamie and D. Stindt, "The Reverse Supply Chain Planning Matrix: A Classification Scheme for Planning Problems in Reverse Logistics," *International Journal of Management Reviews*, vol. 17, pp. 413-436, 2015, doi: 10.1111/ijmr.12046
- [80] H. Zhu, J. Hu and Y. Yang, "Towards a circular supply chain for retired electric vehicle batteries: A systematic literature review," *International Journal of Production Economics*, vol. 282, 2025, doi: 10.1016/j.ijpe.2025.109556

- [81] A. C. Jussani, J. T. C. Wright and U. Ibusuki, "Battery global value chain and its technological challenges for electric vehicle mobility," *RAI Revista de Administração e Inovação*, vol. 14, pp. 333-338, 2017, doi: 10.1016/j.rai.2017.07.001
- [82] M. Rettenmeier, M. Möller and A. Sauer, "Disassembly technologies of end-of-life automotive battery packs as the cornerstone for a circular battery value chain: A process-oriented analysis," *Resources, Conservation & Recycling*, vol. 209, 2024, doi: 10.1016/j.resconrec.2024.107786
- [83] J. Zhuang, A. Bach, B. H. C. van Vlijmen, S. J. Reichelstein, W. Chueh, S. Onori and S. M. Benson, "Technoeconomic decision support for second-life batteries," *Applied Energy*, vol. 390, 2025, doi: 10.1016/j.apenergy.2025.125800
- [84] M. Tajik, S. Yousefi, B. M. Tosarkani and A. Makui, "Digitalization-driven circular economy in battery closed-loop supply chain network design," *Journal of Cleaner Production*, vol. 496, 2025, doi: 10.1016/j.jclepro.2025.145054
- [85] H. van Nieuwenhuijze, K. Chawla, N. Smeets, S. Rongen, L. Visscher, R. Rurup, C. Bernier, S. Gerard, T. Henry, T. Tammet, A. Matruggio, M. Volpini and S. Olsson, "DPP User Stories V3.0," CIRPASS-2 Consortium, 2024.
- [86] B. L. MacCarthy, W. A. Ahmed and G. Demirel, "Mapping the supply chain: Why, what and how?," *International Journal of Production Economics*, vol. 250, 2022, doi: 10.1016/j.ijpe.2022.108688
- [87] Knowledge Based Systems, Inc., "Integration Definition for Function Modeling (IDEF0)," National Institute of Standards and Technology, U.S. Department of Commerce, Gaithersburg, MD, 1993.
- [88] V. Šerifi, P. Dašić, R. Ječmenica and D. Labović, "Functional and Information Modeling of Production Using IDEF Methods," *Journal of Mechanical Engineering*, vol. 55, no. 2, pp. 131-140, 2009.
- [89] J. M. Dorador and R. I. M. Young, "Application of IDEF0, IDEF3 and UML Methodologies in the Creation of Information Models," *International Journal of Computer Integrated Manufacturing*, vol. 13, no. 5, pp. 430-445, 2000, doi: 10.1080/09511920050117928
- [90] J. Rumbaugh, I. Jacobson and G. Booch, *The Unified Modeling Language Reference Manual*, Addison Wesley Longman, 1999.

- [91] A. Kampker, H. H. Heimes, C. Offermanns, M. Frank, D. Klohs and K. Nguyen, "Prediction of Battery Return Volumes for 3R: Remanufacturing, Reuse, and Recycling," *Energies*, vol. 16, no. 19, 2023, doi: 0.3390/en161968731
- [92] C. 2, "DPP User stories V3.0," CIRPASS 2, 2024.
- [93] K. C. Laudon and J. P. Laudon, *Management Information Systems*, Pearson, 2018.
- [94] P. Eleftheriadis, S. Leva, M. Giangi, A. Valdes Rey, A. Borgo, G. Coslop, E. Groppo, L. Grande and M. Sedzik, "Second Life Batteries: Current Regulatory Framework, Evaluation Methods, and Economic Assessment: Reuse, refurbish, or recycle," *IEEE Industry Applications Magazine*, vol. 30, no. 1, pp. 46-58, 2023, doi: 10.1109/MIAS.2023.3325091

A Appendix A

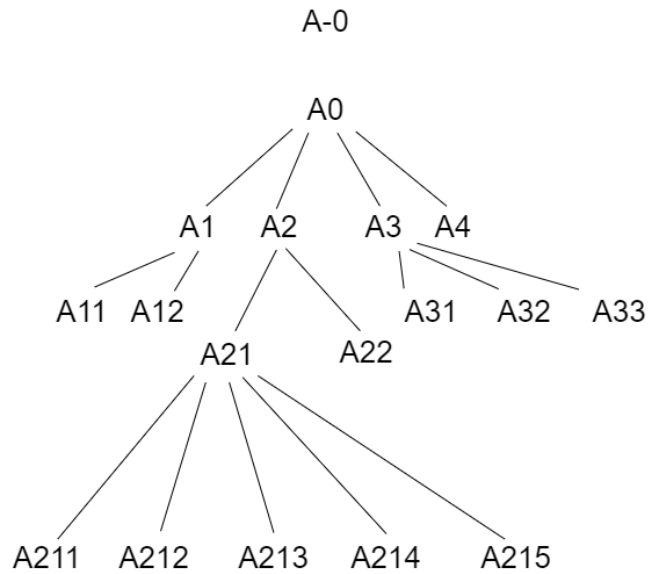


Figure A.1: DSS - node-tree

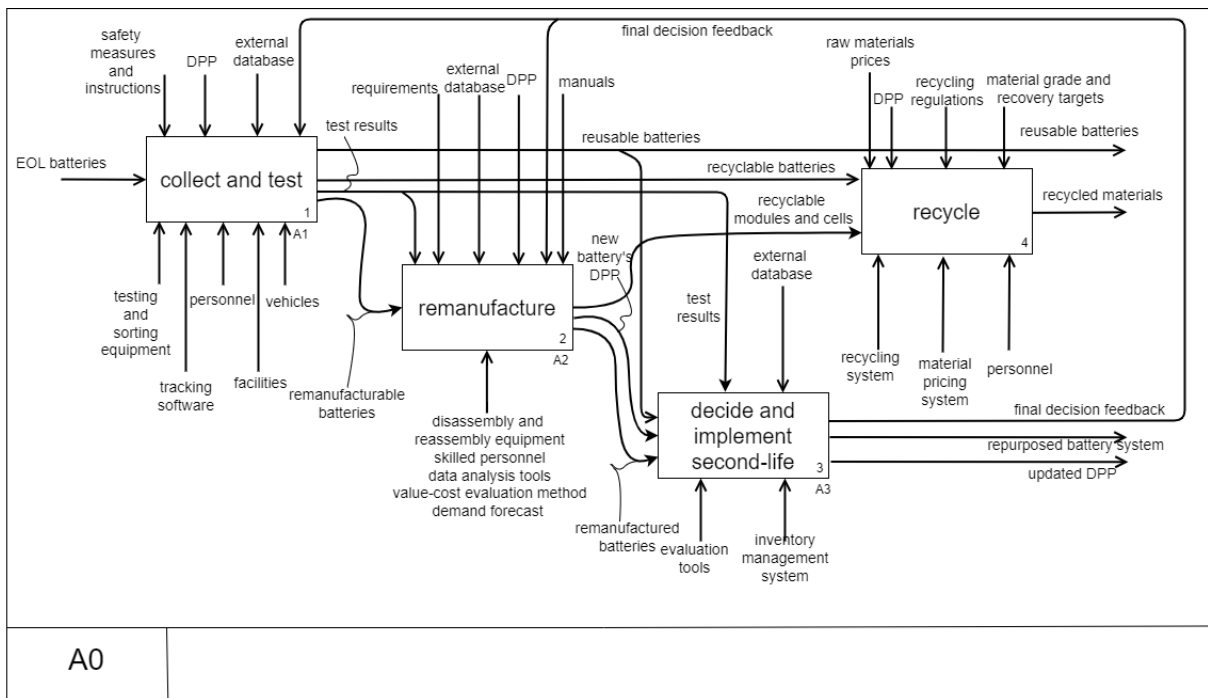


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List of abbreviations

Term	Abbreviation
Battery Energy Storage System	BESS
Battery Management System	BMS
Circular Economy	CE
Database Management System	DBMS
Digital Battery Passport	DBP
Digital Product Passport	DPP
Decision Support System	DSS
European Green Deal	EGD
End-of-Life Vehicle	ELV
End Of Life	EOL
Extended Producer Responsibility	EPR
Environmental, Social, and Governance	ESG
Ecodesign for Sustainable Products Regulation	ESPR
Energy Storage System	ESS
Electric Vehicle	EV
Electric Vehicle Battery	EVB
Greenhouse Gas	GHG
Information & Communication Technology	ICT
Life Cycle Assessment	LCA
Lithium Iron Phosphate	LFP
Lithium-ion battery	LIB

Light Mean of Transport	LMT
Net Zero Emission	NZE
Original Equipment Manufacturer	OEM
Producer Organization	PRO
Responsible Economic Operator	REO
Reverse Supply Chain	RSC
Remaining Useful Life	RUL
Recreative Vehicle	RV
Supply Chain Management	SCM
Second-Life Battery	SLB
Second Life Battery Energy System	SLBES
State of Charge	SoC
State Of Certified Energy	SOCE
State of Health	SoH
Unique Product Identifier	UID
Unified Modelling Language	UML

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