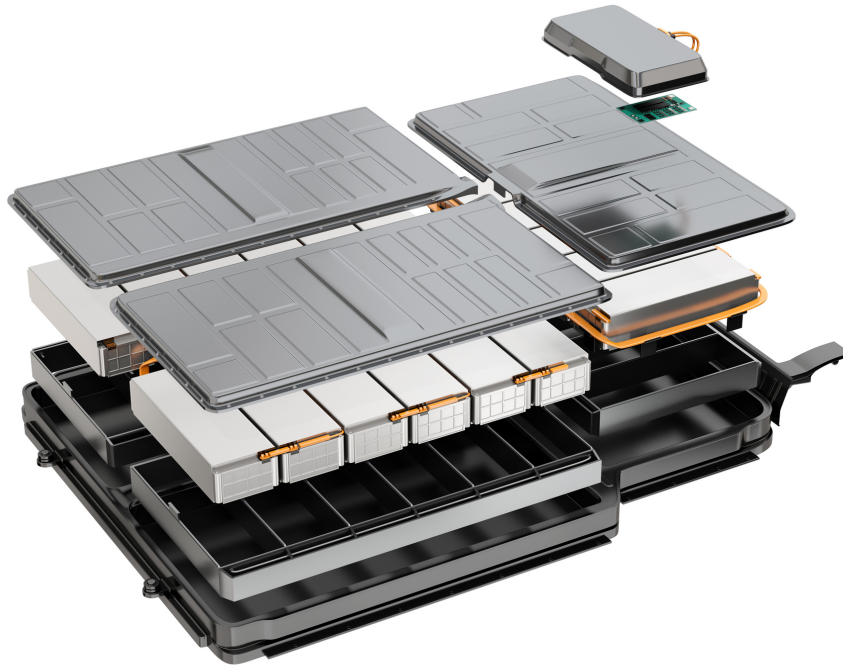




**CHALMERS**  
UNIVERSITY OF TECHNOLOGY



# Closing the Loop: Enabling EV Battery Circularity through Data Transparency

Master's Thesis in Management and Economics of Innovation

Ágúst Heiðar Sveinbjörnsson  
Paritchaya Vejrangsi

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DEPARTMENT OF INDUSTRIAL AND MATERIAL SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2025

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MASTER'S THESIS 2025

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## Abstract

The transition to electric vehicles (EVs) is rapidly accelerating in Europe due to the climate targets and growing demand for sustainable transformation. The rise in EV adoption is increasing the number of batteries reaching end-of-life (EoL), which causes various challenges such as inefficiencies, waste, and safety risks. These issues result from a lack of alignment across the value chain.

This thesis aims to address this misalignment by investigating three research questions: (1) identifying the state-of-art of EoL processes and the its challenges associated with product and data problems, (2) exploring tools and mechanisms enabling data exchange to mitigate these problems, and (3) demonstrating how Battery-as-a-service (BaaS) business model can incentivize data sharing through the identified tools and mechanisms. The thesis applies various qualitative methods, including a systematic literature review, semi-structured interviews with industry experts, and workshops to collect the data.

The findings show that the main barriers to effective EoL management stem from uncircular product designs and limited data transparency across the value chain. Several tools and mechanisms for enhancing data transparency were identified and evaluated using the SWOT framework. The BaaS model was examined through the Circular Business Model Canvas (CBMC) and System Dynamics (SD) modelling, which helped visualize incentive structures for circular designs and collaborations.

Future research should acknowledge that these results are based on the current industry, which is subject to change due to high industry uncertainties and fast-paced developments. Engaging a more diverse group of stakeholders from diverse regions could also strengthen validity of findings. Moreover, key elements of the BaaS model require in-depth analysis to determine their viability and feasibility in different market environments at scale. Finally, quantifying and contextualizing the SD model can provide a strong basis for strategic decision-making.

Keywords: Electric Vehicles, Electric Vehicle Batteries, Circular Economy, Design for Circularity, End-of-Life Management, Battery Disassembly, Data Exchange, Battery-as-a-Service



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Ágúst Heiðar Sveinbjörnsson, Gothenburg, June 2025

Paritchaya Vejrangsi, Gothenburg, June 2025



# List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AI	Artificial Intelligence
BaaS	Battery-as-a-Service
BMS	Battery Management System
BoL	Beginning-of-Life
B2U	Battery Second Use
CBMC	Circular Business Model Canvas
CEBM	Circular Economy Business Model
CE	Circular Economy
DPP	Digital Product Passport
DfC	Design-for-Circularity
EoL	End-of-Life
EU	The European Union
EV	Electric vehicle
IoT	Internet of Thing
MoL	Middle-of-Life
NMC	Nickel Manganese Cobalt
NCA	Nickel Cobalt Aluminum
OEM	Original Equipment Manufacturer
PSS	Product-Service-System
RUL	Remaining useful life
SoC	State-of-Charge
SoH	State-of-Health
SoR	State-of-Resistance
TMS	Thermal Management System



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# 1

## Introduction

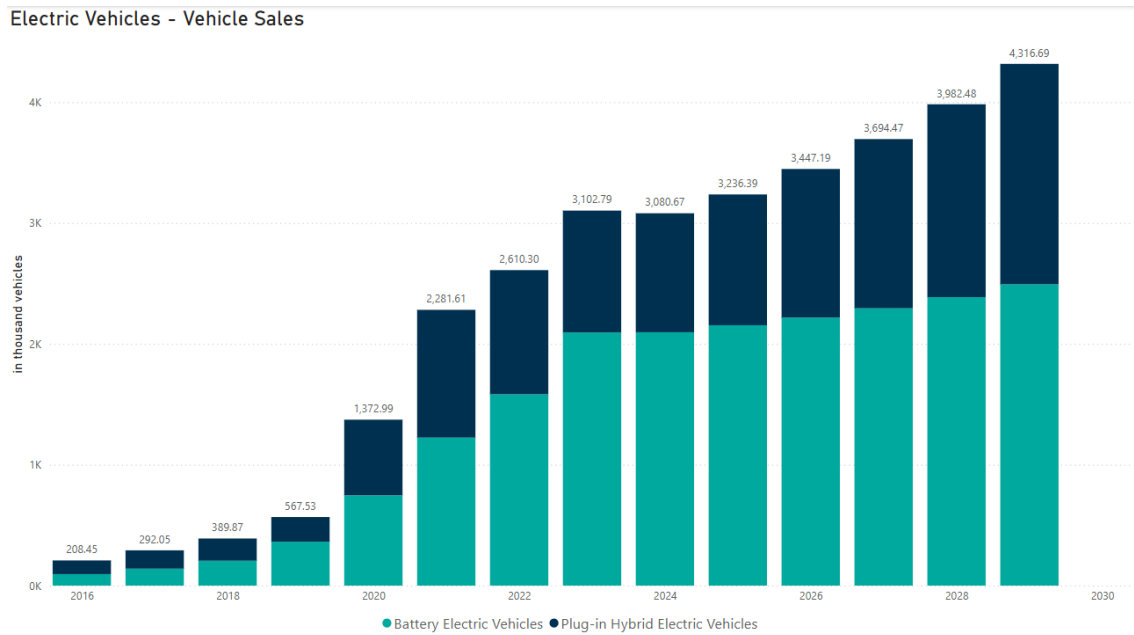
### 1.1 Background

The transportation industry is one of the largest energy consumers in the world. It is also one of the largest contributors to increased CO<sub>2</sub> emissions and air pollution (Gopalakrishnan & Govindan, 2021). With increased awareness of climate change and the goal to meet the Paris Agreement 1.5C target, the European Union (EU) has set ambitious goals to switch towards sustainable transportation. One of the policies is banning the sales of petrol and diesel cars by 2035 (European Parliament, 2022). Shifting to electric vehicles (EVs) could be the major driver in lowering emissions in the transportation and power sector by 30% (World Economic Forum, 2020). As a result, new registrations of EVs in the EU have grown significantly since 2020 (European Environment Agency, 2024) and are expected to grow even further in the coming years (Jose et al., 2024). This rapid expansion will result in more batteries on the road, but more importantly, will lead to more End-of-life (EoL) batteries (McKinsey and Company, 2023). Figure 1.1 illustrates the growth of EV sales in the coming years.

This increased demand growth created an even greater demand for some critical raw materials, such as nickel, cobalt, aluminum, magnesium, copper, titanium and manganese. The majority of these are included in the European list of critical raw materials (CRMs) (European Commission, n.d.), as they are essential for battery production (Bhutada, 2022). Those shortages could cause supply disruptions and price volatility. In addition, their mining and processing not only have serious negative impacts on the environment but also raise social concerns regarding human rights abuses (Mayyas et al., 2019). Therefore, these challenges call for the development of sustainable initiatives that maximize resource efficiency and minimize waste through narrowing, slowing, and shifting from a linear to a closed-loop supply chain (Bocken et al., 2016; Guide Jr & Van Wassenhove, 2009). This circularity strategy can be carried out through various methods including reusing, recycling, and refurbishing (European Parliament, 2023).

## 1. Introduction

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**Figure 1.1:** Sales of all EVs and forecasted futuresales as of November 2024 (Statista, 2025)

Despite growing economic and environmental demands for battery circularity, battery disassembly at their EoL remains challenging due to various factors (Ai et al., 2024; European Parliament, 2023; Schmidt & Lienemann, 2023). Additionally, misalignment and lack of transparency among value chain actors worsen the issue. Battery designs, for example, are often not designed with disassembly and circularity in mind, leading to significant issues when the battery reaches its EoL.

Applying Design for Circularity frameworks could be a potential strategy to address the misalignment between battery design and EoL processes. These principles can enhance disassembly efficiency, material recovery, and sustainability from production to EoL management according to many scholars and professionals (Accenture, 2023; Ellen MacArthur Foundation, n.d.; Wang et al., 2022)

However, achieving this alignment requires data exchange between different stages of the supply chain. A potential solution lies in the implementation of Digital Product Passport (DPP), which will become an EU legal requirement starting in 2027 (European Parliament and Council of the European Union, 2023). DPPs are unique product identifiers, in which information about each unit can be stored (Harper et al., 2022). Specific data requirements, including basic manufacturing information, raw materials and compositions, as well as performance and durability are outlined in the regulation (Battery Pass Consortium, 2023). All these data points collected from the BoL (Beginning-of-Life) to EoL stages must be seamlessly integrated (Cardenas-Sierra et al., 2025). This poses a new challenge for the EV

battery industry, as battery designers are often hesitant to share this information due to competitive reasons and confidentiality concerns (Berger, Rusch, et al., 2023). In addition, DPPs only carry information down the supply chain. Meanwhile, designers and assemblers do not receive vital data from EoL actors through the DPP. To enhance sustainability and achieve a circular economy (CE), it is therefore crucial to understand how different data sharing mechanisms foster collaboration across the value chain and how they can be incentivized for increased data transparency.

## 1.2 Aim and Research Question

This thesis investigates how increased alignment and circularity within the EV battery value chain can solve the problems plaguing EoL actors and increase competitiveness of participating actors. This is investigated by identifying which issues are plaguing EoL actors, what tools and mechanisms could mitigate these issues and how the implementation of these tools and mechanisms can be incentivized through business model innovation. We will solely focus on the EV battery industry in the EU. Thus, the research questions that will be examined are:

*RQ1: What limits the efficiency and effectiveness of current EV battery disassembly practices?*

*RQ2: What tools and mechanisms could enhance data transparency for better EV battery EoL process performance?*

*RQ3: How can Battery-as-a-service (BaaS) support and incentivize data exchange within the EV battery value chain?*

## 1.3 Deliverables

In alignment with research questions, the deliverables are as follows:

1. An overview of EV battery disassembly practices and design and data-related challenges.
2. A list of data exchange mechanisms, including their strengths, weaknesses, opportunities, and threats.
3. Circular Business Model Canvas (CBMS) defining BaaS and a System Dynamic (SD) model illustrating its effects on circularity.

## 1.4 Thesis structure

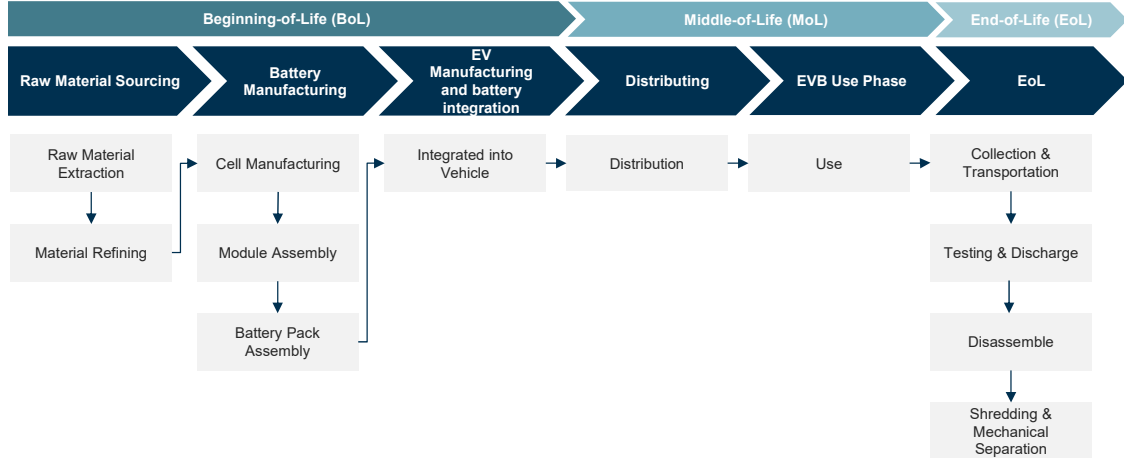
The thesis includes six main sections. Introduction introduces the context of the thesis and motivates its relevance to the current industry. This section also contains our aim statement and research questions. Theory serves as the theoretical foundation of the thesis. It defines key terms and regulations that play a key role in the industry. Methods describe our methodology used in this thesis. This contains all our methods of data collection, data analysis, confidentiality information and an AI statement. Results describe our findings regarding the three research questions and deliverables. It contains the current EoL management and disassembly practice alongside their problems, data exchange mechanism identification an evaluation through SWOT analysis and an illustration of how BaaS can incentivize data transparency and circularity. Discussion reflects on the methodology we adopted along with their limitations and potential drawbacks. It also contains the implications of the findings. Conclusion summarizes the key learnings and messages from this thesis and proposes next steps.

# 2

## Theoretical Background

### 2.1 The EV Battery Value Chain

The value chain for EV batteries is a complicated and multistage system. The typical linear EV battery value chain starts from raw material extraction to EoL management (Nordic Council of Ministers, 2024; Ribeiro da Silva et al., 2023). At a high level, as is presented in Figure 2.1, the value chain typically includes six steps as follows: (1) Raw material sourcing, (2) Battery manufacturing, (3) EV manufacturing and battery integration, (4) Distribution, (5) Use and (6) EoL handling.



**Figure 2.1:** Linear EV Battery Value Chain, based on the portrayals of Ribeiro da Silva et al. (2023) and Nordic Council of Ministers (2024). Along with the battery lifecycle phases discussed by Pohlmann et al. (2024)

In the linear EV battery value chain, the battery has three distinct lifecycle phases. Those are the BoL phase, the Middle-of-Life (MoL) phase and the EoL phase. The BoL phase consists of all process steps from raw material extraction until the battery has been assembled and implemented. This includes the battery design process. The MoL phase begins at the distribution stage and lasts throughout

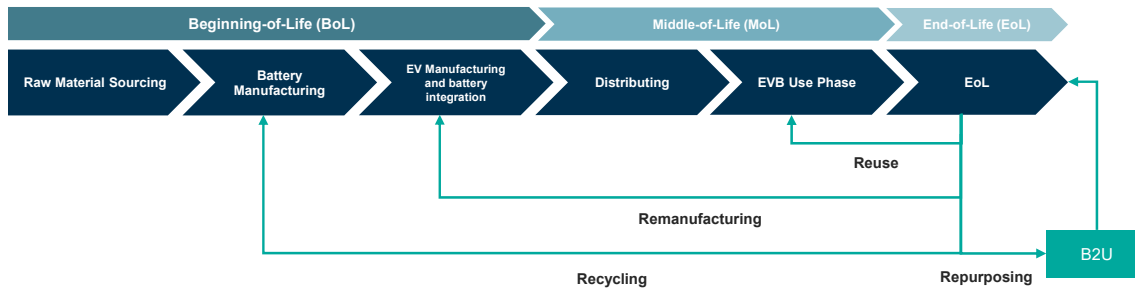
its use. When the battery can no longer be used, it has reached its EoL stage (Pohlmann et al., 2024).

## 2.2 Circular Economy

The circular economy (CE) principle aims to increase resource efficiency while minimizing environmental impacts by keeping the resource in the loop as long as possible. In other words, these principles encourage thinking from cradle to cradle rather than cradle to grave. Although, some do debate that the goals of CE aim to promote improved economic performance rather than strictly sustainability perspectives (Geissdoerfer et al., 2017; Kirchherr et al., 2017), these initiatives can be achieved through resource flow strategies in sustainable supply chain management that promote narrowing, slowing, and closing of resource flows (Geissdoerfer et al., 2017).

The narrowing strategy aims to increase resource efficiency by using fewer resources. Slowing down is a strategy for extending a product’s lifespan for as long as possible. The closed loop focuses on returning products and materials back into the production cycle after the product reaches its EoL. These three sustainability principles comply with the 9-R framework (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover), which also encourages the transition from a linear economy to a circular economy (Geissdoerfer et al., 2017; Kirchherr et al., 2017).

By aligning resource flow strategies with CE concepts, Circular Economy Business Models (CEBMs) can be an opportunity for companies (Lüdeke-Freund et al., 2019). Narrowing complies with more innovative product use and manufacture since it focuses on using fewer raw materials during production. The strategies are Rethink, Redesign, and Reduce. Slowing extends product lifetime, comparable to strategies that prolong the product life such as Reuse, Repair, Remanufacturing, and Repurposing. When a battery receives any of these treatments, they are in the battery lifecycle phase named Battery second use (B2U). That phase contains all the processes from when batteries are adjusted to second life application until they reach their second EoL. Closing the loop sends materials and products back into the manufacturing loop rather than to waste, and it is achieved through Recycling and Recovery. By integrating these concepts, the EV battery industry can reduce material consumption, extend battery life span, and improve valuable material recovery, maximizing sustainability and circularity. A representation of a closed loop EV battery value chain can be observed in Figure 2.2



**Figure 2.2:** Closed loop EV Battery Value Chain, based on the portrayals of Ribeiro da Silva et al. (2023) and Nordic Council of Ministers (2024). Along with the portrayal of circular strategies proposed by Börner et al. (2022)

As CE gains more traction, the need for sustainable design strategies has grown alongside it. One of these design strategies is design for circularity (DfC). DfC revolves around designing products in such a way that their components/modules can be easily and non-destructively separated at the product’s EoL. Thus, the product can be reused, remanufactured, repurposed or recycled (Chakravorty & Rao, 2023; Formentini & Ramanujan, 2023)

### 2.3 CE of EV batteries

The CE concept is vital to the EV industry since batteries are composed of valuable raw materials, which leads to supply risk (Mayyas et al., 2019). Embracing the concept of CE strategies to maximize resource flow and minimize waste is crucial for stakeholders in the value chain to gain economic advantage and achieve sustainable development. Research by Schulz-Mönninghoff et al. (2023) shows that automotive manufactures can increase material circularity of critical battery material from 5% to 23% by 2030 by adopting closed-loop production and different end-of-life strategies. Although there are various approaches to achieving CE in general, existing CE strategies for EV batteries include repairing, repurposing for second-life applications, remanufacturing, and recycling.

Maintenance and repair, which allow batteries to last longer in their first life, have become the minimum services offered by automotive companies. Furthermore, another strategy to extend product lifecycles, such as remanufacturing and repurposing, presents significant market potential for the recovery of electric vehicle batteries in the near future (Alamerew & Brissaud, 2020).

Moreover, repurposing EV batteries for second-life applications is already being implemented in grid storage solutions such as *the Tesla Powerwall* and *the Nissan xStorage*. Even though second-life applications may reduce the demand for recycling (Nurdiawati & Agrawal, 2022), batteries will ultimately reach their end of life. Thus, recycling is essential for achieving CE.

Olsson et al. (2018) claim that one outlook of CE of EV batteries is transitioning from a linear recycling model to optimized recycling. This involves moving from manual EoL processes to automated ones with large-scale operations. However, several barriers, including business initiatives and potential (Cognitive barriers), collaborative ecosystem (Organizational barriers), and unstandardized design of batteries (Technological Barriers), hinder second-life practices and improved recycling capabilities. Thus, Baazouzi et al. (2021) argues that disassembly should be prioritized in battery system design, highlighting its importance. They further emphasize that efficient disassembly is vital to unlocking circularity, especially given the rapidly increasing volume of EV batteries approaching their EoL.

## 2.4 Battery Regulations

To combat climate change, the EU has constructed new climate goals and regulations to be implemented in the coming years.

### 2.4.1 European Green Deal/Climate Goals

The European Green Deal is a social transformation plan within the EU that contains several policies to reach specific climate goals. Although these goals are not specified only for batteries, they are highly relevant to be able to achieve these goals. These goals include having a 55% reduction in the emission of greenhouse gases by 2030 and ultimately having no net emissions by 2050. By 2030, at least 42,5% of total energy consumption should be from renewable sources and by 2035, the sales of diesel and petrol cars will be banned (European Commission, 2019). To support the push towards the climate goals, the EU has introduced new sustainability regulations, including the new EU Battery Regulation.

### 2.4.2 EU Battery Regulation

To help reach their ambitious climate goals, the EU introduced a new regulatory framework called Regulation (EU) 2023/1542, generally called the EU Battery Regulation. This new regulation replaces the Battery Directive (2006/66/EC), and

contains a large number of updates to better match the EUs climate ambitions. In this regulation, five different types of batteries are identified, one of them being EV batteries. The EU believes that replacing internal combustion engine vehicles with electric vehicles is one of the key prerequisites to reach the climate neutrality goal described above. However, the production and handling of EV batteries come with their own problems, for example, concerning raw materials and end-of-life management. To combat this, the regulation issues several requirements for EV batteries (European Parliament and Council of the European Union, 2023).

To track the emissions generated in the lifecycle of the EV batteries, the regulation requires the declaration of the emissions of every battery model and every manufacturing plant (Article 7). This information is tracked and documented throughout the entire supply chain of the battery, from the extraction of raw material until its eventual disposal. For EV batteries this should be implemented on the 18th of February 2025. This article also mentions a variety of other information also to be declared in the same way as the emissions, for example location information and battery model information (European Parliament and Council of the European Union, 2023).

To reduce the industrys dependency on virgin raw materials, and therefore support a circular battery economy, the EU has defined mandatory recycled content amount in each manufactured battery (Article 8). The implementation of this policy has two deadlines for manufacturers to reach their goals, the first one being the 18th of August 2031 and the second one being the 18th of August 2036 (European Parliament and Council of the European Union, 2023). The minimum recycled contents at both of these deadlines can be found in Table 2.1.

**Table 2.1:** The minimum requirement of recycled materials for each manufactured battery for each deadline set in the EU Battery Regulations.

Deadline	Cobalt	Lead	Lithium	Nickel
August 2031	16%	85%	6%	6%
August 2035	26%	85%	12%	15%

These targets are subject to change, as mentioned in Article 8. No later than 31st of December 2028, the Commission should have assessed if these targets require tweaking. If the targets are to be changed, for example due to improved technology for recovering these materials, the Commission will have the new targets defined no later than on the 18th of August 2029.

Article 56 discusses extended producer responsibility (EPR). The producer mentioned in the title of this article is defined as the supply chain actor that brings the battery to the market. In the case of EV batteries, it is mainly the original

equipment manufacturers (OEMs) that bear this responsibility at the BoL for batteries. This requires the producers to be responsible for the financing/organization of the EoL handling of batteries. This includes the collection of waste batteries, their sorting, treating and recycling. These operations all have defined requirements (ANNEX XII). One of the requirements is recovery rates of materials in batteries (European Parliament and Council of the European Union, 2023). The defined targets for all deadlines can be found in Table 2.2.

**Table 2.2:** Minimum material recovery rates for each manufactured battery for each deadline set in the EU Battery Regulations.

<b>Deadline</b>	<b>Cobalt</b>	<b>Copper</b>	<b>Lead</b>	<b>Lithium</b>	<b>Nickel</b>
31 Dec 2027	90%	90%	90%	50%	90%
31 Dec 2031	95%	95%	95%	80%	95%

The information above for EV batteries, amongst other, should be accessible via a DPP (Article 77). The actor who places the battery on the market is responsible for the accuracy and completeness of the information embedded in the passport. The contents of the passport are outlined in Annex XIII of the Battery Regulation, where certain stakeholders have the right to access certain information (European Parliament and Council of the European Union, 2023). Further specifications for the DPP will be discussed later in the thesis.

# 3

## Methods

In this thesis, multiple data sources are collected to increase credibility and construct validity (Yin, 2018). This includes literature, interviews, site visits, and workshops. Each method for data collection and analysis is described in the following sections.

### 3.1 Literature Review

A systematic literature thesis is beneficial for understanding key concepts and relevant theories regarding the research topic (Bell et al., 2022; Snyder, 2019). This step also helps gather information on current research and identify gaps in previous studies (Bell et al., 2022; Snyder, 2019). As described by Moher et al. (2009), the literature review for this thesis follows the PRISMA guidelines to enhance the transparency and reliability of the review process.

The primary databases for data gathering are Scopus and the Chalmers Research Library. These platforms contain a large amount of articles and publications, many of high credibility. Although news and internet sites can provide up-to-date information that is highly likely to be beneficial for the fast-paced market industry, such as EV batteries, their reliability must be carefully evaluated by checking for potential biases, verifying authors' credentials, and considering the publisher's reputation (Bell et al., 2022). Thus, academic sites, government reports, and non-profit institutions are more reliable and are prioritized in this thesis.

The search for academic papers begins with determining the domain and initial search terms. Since we have three different questions, with minimal overlap, three search strings had to be crafted. The search strings are shown in Table 3.1. Then, we set a publication time frame, which includes studies from 2015 onward. The reason is that battery technology and the EV market have accelerated since then (Elg et al., 2020). However, search terms were adjusted along the way to improve the coverage and relevance of the information.

**Table 3.1:** Search Strings and Number of Results for Each Research Question

RQ	Search String	Number of Results
RQ1	( "electric vehicle batter*" OR "EV batter*" OR "lithium-ion batter*" OR "traction batter*" ) AND ( "disassembl*" OR "dismantl*" OR "battery end-of-life" ) AND ( "challenge" OR "barrier*" OR "data exchange" OR "disassembly process*" OR "disassembly practic*" OR "dismantling process*" OR "dismantling practic*" )	181
RQ2	( "electric vehicle batter*" OR "EV batter*" OR "lithium-ion batter*" OR "traction batter*" ) AND ( "digital battery passport" OR "digital product passport" OR "data exchange" OR "information exchange" )	49
RQ3	( "electric vehicle batter*" OR "EV batter*" OR "lithium-ion batter*" OR "traction batter*" ) AND ( "business model*" OR "product-service system" OR "servitization" OR "take-back" OR "battery leasing" ) AND ( "circular economy" OR "circularity" OR "sustainab*" )	94

The overall results from the systematic literature review for all three research questions are demonstrated in Fig 3.1. Take RQ1 for example, the initial search results in a total of 181 papers. After titles and abstracts of these remaining references were then screened, some papers were excluded due to their in-depth focus on chemistry and mechanical optimization. As a result presented in Figure 3.1, 50 papers were retained.

Next, a full-text screening process was conducted following the defined criteria, and the eligible articles were recorded. This process will be iterated until it reaches saturation. In other words, this process ended when the new paper could not provide significant insights (Bell et al., 2022). Ultimately, this process for RQ1 resulted in 17 references.

Additionally, snowballing strategies are used to expand the coverage and find additional relevant sources by looking into the reference lists of popular publications (Bell et al., 2022). This thesis also includes articles recommended by supervisors and industry experts.

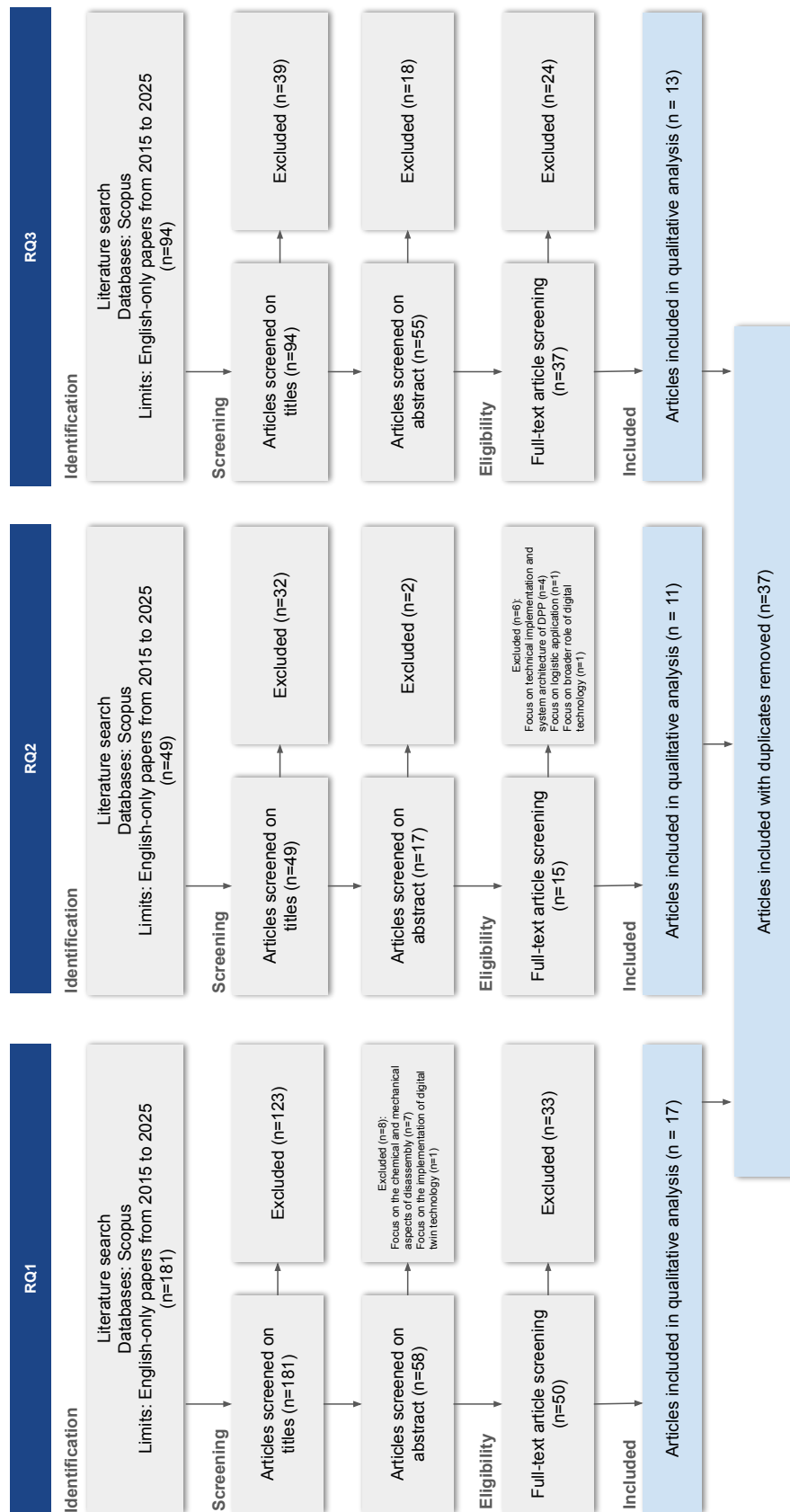


Figure 3.1: PRISMA Flow Diagram

## 3.2 Participant Selection

There are many direct and indirect actors that are involved in the value chain of EV batteries. Direct stakeholders are those involved in EV production, in the use phase, and EoL applications. This includes cell and battery pack manufacturers, OEMs, car dealerships, consumers, disassemblers, and recyclers. Indirect stakeholders act as ecosystem enablers, such as policymakers, research scholars, and support companies. They are also considered in this thesis to enable a broader perspective of the CE ecosystem for EV batteries and address research questions on DfC, data exchange issues, and CEBMs.

To select experts for expert interviews, stakeholder analysis was performed to prioritize and determine stakeholders in the EV battery ecosystem. The Power-Interest Grid developed by Bryson (2004) is a well-known tool for this sort of analysis. It is divided into four quadrants based on the combination of potential power and interest. As a result, it can be prioritized as follows:

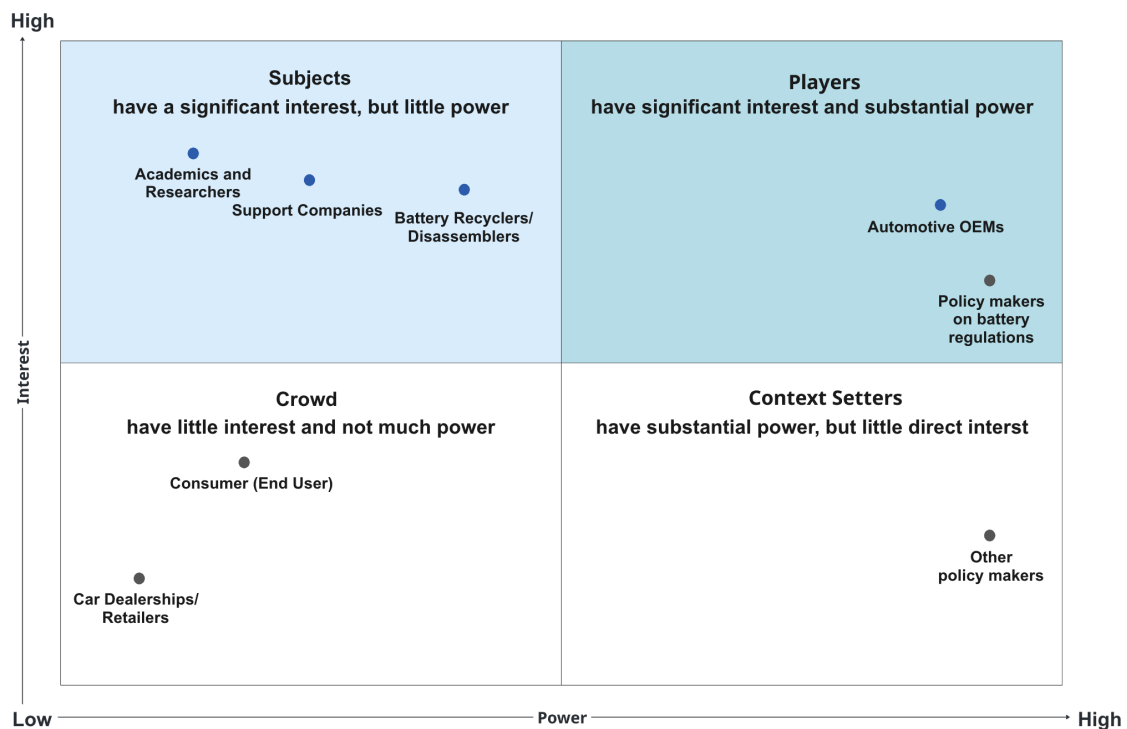
1. **High Power, High Interest:** Key stakeholders with a direct impact on automobiles, battery design, recycling, and CE efforts. They should be prioritized for future interviews.
2. **Low Power, High Interest:** Stakeholders who are interested in EV circularity but with limited power to drive large-scale change. They can provide specialized expertise in the EV industry and sustainability perspectives.
3. **High Power, Low Interest:** Stakeholders who influence policy and industry adoption but do not focus only on the EV battery industry. Although they can provide high-level insights, they are not as important as the two previously stated groups.
4. **Low Power, Low Interest:** Stakeholders with minimal influence and interest in this field. They are not critical for this research.

By applying the Power-Interest Grid framework, shown in Figure 3.2, the focus is placed on the five actors located in the top two quadrants:

1. **OEMs and Battery pack designers:** These stakeholders have both high power and high interest in driving lithium-ion circularity (Wrålsen et al., 2021), as they lead the battery design processes and play a significant role in increasing circularity.
2. **Governments or Policymakers:** These stakeholders, who define regulations like the Battery Regulations, also have a high impact and interest in circularity of lithium-ion batteries (Wrålsen et al., 2021). However, with limitations in connecting to these actors, the results from this group will rely on existing

regulations and publications.

3. **Battery Disassemblers and Recyclers:** They face difficulties in disassembling and recycling battery packs due to a lack of data and product design that does not support efficient disassembly. While they are highly interested in circular product design and data sharing, they have limited power to influence upstream players such as battery pack designers and OEMs.
4. **Support companies (Consultancies and System integrators):** These stakeholders seize many opportunities to tackle these challenges, but still have limited resources and power over the supply chain. In addition, they can also provide extensive knowledge in specific subjects.
5. **Academic researchers:** They have a strong interest in this thesis and show in-depth knowledge. However, they do not have the power to implement practical implications.



**Figure 3.2:** Power-Interest Grid for Participant Selection (EV Battery Industry)

Next, companies and individuals belonging to the top two quadrants are short-listed for potential engagement. Purposive sampling is employed as an initial approach to reach out to interviewees who have professional experience in circular product design and EoL management for EV batteries (Bell et al., 2022). Furthermore, snowball sampling, a technique where existing participants recommend other potential participants, is also used to expand coverage to relevant people and

strengthen the findings (Bell et al., 2022).

The shortlisted potential participants were contacted via email or through the networks of our supervisors with an attached one-page summary of the project goals and interview guidelines. In addition, a 44.12% was recorded to assess the thesis's engagement and interest in this research topic among industry professionals.

### 3.3 Interviews

Expert interviews are a qualitative method that provides deep insights into industry knowledge, professional perspective, and expectations (Bell et al., 2022). The semi-structured interview approach allows participants to provide detailed responses to predetermined questions while allowing for more flexibility by exploring relevant topics (Bell et al., 2022). In addition, this approach can be used alongside the literature review to validate the current findings and gather additional detailed information that is not readily available in academic papers and public sources.

#### 3.3.1 Interview Questionnaire

Interview questionnaires were designed to address the three research questions. The questions were formulated from previous knowledge gained through comprehensive literature reviews, which followed an inductive approach (Bell et al., 2022). Additionally, the PESTEL framework, including Political, Economic, Social, Technological, Environmental, and Legal factors, was used to assist in trying to get full coverage for the questions. The questionnaires were also customized based on the expertise of those actors in the value chain within the scope of the research questions.

Additionally, Kvale's criteria for successful interviewing such as being knowledgeable, structuring, and clear were applied throughout the interview process (Kvale, 1994). Moreover, consideration for balanced questioning and ethical sensitivity are also taken into account as recommended by Bell et al. (2022).

In this thesis, a total of 15 participants were interviewed. These included professionals from various segments of the EV battery ecosystem, which are prioritized in the top quadrants of stakeholder analysis: OEMs, Recyclers, Research Institutes, Digital Platform Providers, and Consultants. However, due to the time frame and feasibility limitations, policymakers were not engaged in this thesis. A list of all interview experts can be found in Table 3.2. Interview referrals are formatted as [Expert #]. The interviews were conducted in several different locations. The count of each type can be seen in Table 3.3.

**Table 3.2:** List of the Expert Interviewees

#	Actors	Interviewee Role	Format
A	Automotive OEMs	Battery Designer	Online
B	Battery Recycling Firm	Operation Manager	Site Visit
C	Battery Recycling Firm	CEO	Online
D	Research / Battery Industry	Academic Researcher	Online
E	Research / Battery Industry	Academic Researcher	Site Visit
F	Researcher / Consumer Electronics	Academic Researcher	In-person
G	Consulting Firm	Circular Design Engineer	Online
H	Solution Provider	CEO	Online
I	Solution Provider	Research Engineer	Online
J	Automotive OEMs	Business Owner	Online
K	Researcher / Supply and Operations Mgmt	Academic Researcher	In-person
L	Researcher / Circular Economy	Academic Researcher	Online
M	Disassembling Firm	R&D Specialist	Online
N	Researcher / Circular Economy	Academic Researcher	Online
O	Truck OEM	Research Manager	Online

**Table 3.3:** Number of Interviews by Format

Format	Count
Online interview	11
Site visit	2
In-person interview	2
Total	15

### 3.3.2 Interview Execution

This process lasted from February to April 2025. The interviews were conducted both online and in-person. While the online interviews were facilitated through Microsoft Teams, in-person interviews were held at participants workplaces. The duration of each interview varied from 30 to 60 minutes, depending on the participant’s schedule and the depth of their knowledge. Regardless of the interview format, all conversations were recorded in Microsoft Teams to ensure detailed and precise transcription for analysis (Bell et al., 2022). Alongside the recording, meeting notes were made simultaneously to assist in the analysis.

Complementing the individual interviews, two site visits were carried out at the battery recycling plant and the institutions laboratory. Each site visit lasted two hours approximately. These visits provided an opportunity to observe the actual disassembling and recycling process, which goes beyond findings collected from academic papers and verbal interviews.

Regarding ethical considerations, all participants received detailed information

about the thesis's aim, format, and confidentiality before the interview. Consent regarding confidentiality was agreed upon at the beginning of the interviews, along with consent to record. All participants were assured anonymity and confidentiality. Before publishing the report, the preliminary findings and direct quotations represented in the report were also shared with the respective participants for validation and approval. This process not only increases the accuracy of interpretation but also strengthens the quality of the research, as emphasized by Yin (2018).

#### 3.3.3 Interview Data Analysis

The transcripts from these interviews are our primary source of qualitative data from the interviews, with the recordings themselves being used in a support context to validate the accuracy of the transcript. All interviews were conducted in English, so no translation was performed in the analysis.

For the first round of interview analysis, we took an inductive approach. That means there was not a preexisting coding frame that we tried to fit our data into, but rather that codes and themes emerge as patterns are recognized in the data. To perform the data analysis in this approach, we used the 6-step thematic analysis, which was proposed by Braun and Clarke (2006). The process is as such:

1. **Familiarizing yourself with your data:** This includes transcribing, reading and re-reading the data to improve understanding.
2. **Generating initial codes:** Key messages and learnings are highlighted.
3. **Searching for themes:** Patterns are recognized and explored. Related codes are grouped into themes.
4. **Reviewing themes:** The themes are reviewed and the final theme outlook is decided.
5. **Defining and naming themes:** The themes are given names that describe the content of their embedded codes.
6. **Producing the report:** The findings from the analysis are presented.

An example of a theme that was derived from the data following this process can be observed in Table 3.4:

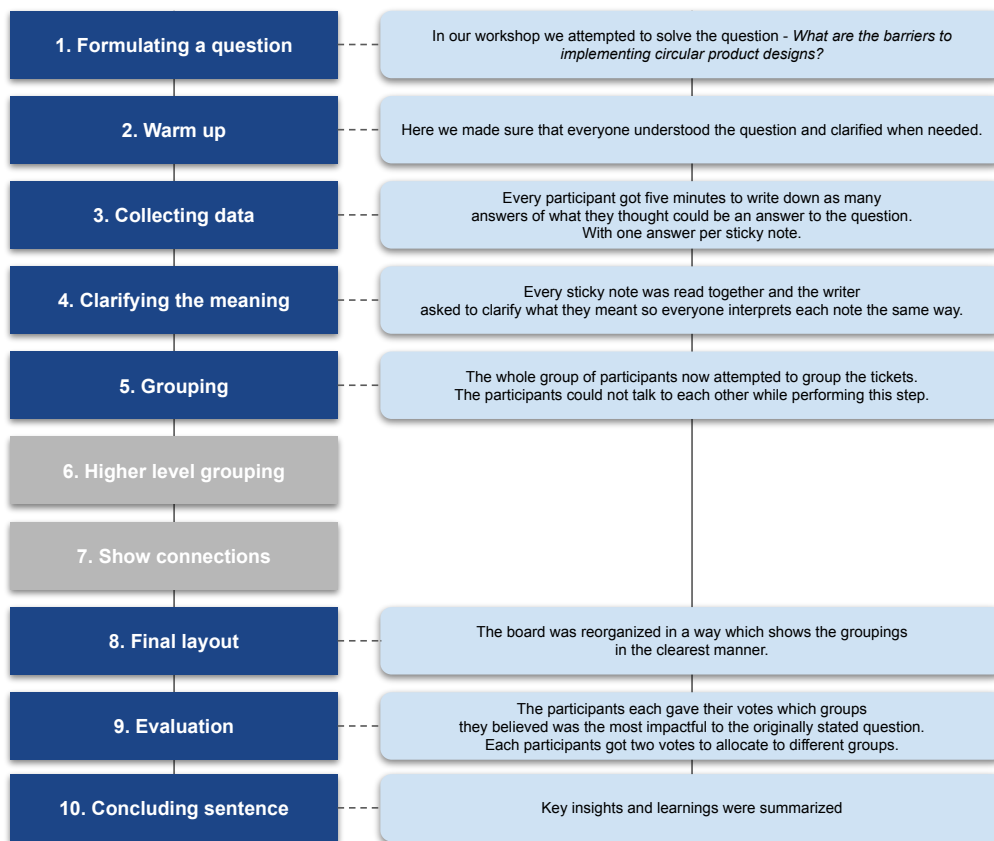
**Table 3.4:** Demonstration of a first and second order theme along with their insights as a result of thematic analysis of the interview data

Second Order Theme	First Order Theme	Key Insight
Design problem	Design parameter prioritization	Different design parameters have higher priority than circularity, leading to uncircular designs.
Data problem	Sensitive data	High data sensitivity disables data sharing, especially when lacking regulation/incentives
EoL problem	Safety issues of battery handling at their EoL	The lack of battery data and the varying condition of the arriving batteries can lead to safety concerns when handling batteries

### 3.4 Workshop

In this project, we had the opportunity to participate in an EV battery seminar and orchestrate a workshop with several experts in the EV battery industry, most of whom were researchers. The seminar included a presentation in which the contents of the project were presented, and the audience could then ask questions and provide feedback.

The workshop itself had eight participants. It was designed following the Affinity-Interrelationship Method (AIM). The AIM method is a problem-solving tool to help analyze complex qualitative data, where the team attempts to solve a broad question. The method is used when the workshop contains several people, each equipped with a pen and sticky notes. It is based on the 19-step approach, proposed by Professor Shoji Shiba, but narrows the steps down to ten (Alänge, 2009). Due to time constraints in the workshop, some modifications had to be made to the process for it to fit our timeframe. Figure 3.3 showcases the steps of the AIM method along with how we implemented these steps to fit our time frame.



**Figure 3.3:** Steps of the AIM Method (Left) (Alänge, 2009) and their implementation in this thesis (Right)

## 3.5 Circular Business Model Canvas (CBMC)

For RQ3, which explores how BaaS supports data exchange between EoL and BoL actors in the EV battery value chain, the CBMC is used as the primary analytical framework. This framework can present how a business creates, delivers, and captures value with and within a closed material loop (Mentink, 2014).

In this thesis, the CBMC developed by Lewandowski (2016), built on top of the original Business Model Canvas by Osterwalder and Pigneur (2010), is used to analyze circular business model elements in the BaaS context. It contains eleven components listed below:

1. **Value proposition(s):** This presents the core value offered to target users, including incentives to return used products. Creating circular value propositions could involve offering a product, product-related service, or service.
2. **Customer segments:** Target customer must fit the value proposition
3. **Customer relationship:** Depending on consumer preferences and needs, it

involves social media promotion and cooperation with local partners when advanced recycling is required.

4. **Key activities:** The main activities that either directly or indirectly result in the development, provision, and delivery of circular value propositions. These could be increasing performance, product design, technology exchange, remanufacturing, recycling, or lobbying.
5. **Key channels:** Channels are means used to communicate or deliver value propositions. Virtualization is one of the significant transitions in the circular business model.
6. **Cost Structures:** This refers to the cost required to operate the business model. The change in cost structure can affect reorganization, such as materials, energy consumption, and employee mindset.
7. **Revenue stream:** The way how business model can monetize which directly link to value proposition. From the CE perspective, the resources retrieved from material loops can also generate revenue.
8. **The take-back system:** The take-back management system must consider its distribution channels as well as customer relations.
9. **Adoption factors:** Organizational capabilities and external factors should be taken into account to achieve a CE.

### 3.6 System Dynamics Modelling

System dynamics (SD) is a conceptual framework and modelling approach for complex systems. It offers a strong foundation for visualizing and analysing the structure of the system at hand. It also offers simulation potential, meaning that behaviours can be analyzed over time, highlighting key drivers of behavior in the system. In this thesis, no simulation was performed due to time and information constraints. Instead, a system dynamics stock-and-flow diagram was crafted to illustrate how certain key variables affect the system and how they are affected themselves (Sterman, 2002).

There are a few different variables types in SD. Stock variables are accumulations or the level of resources at a given time. An example these accumulations are inventory or population, and the value allocated to the variable indicates the system state at a given time point. The value of stock variables can only be changed by flow variables. Flows are the rates at which stocks increase and decrease. For instance, in a country population model, the change in the stock variable Population could be changed by the inflows, births and immigration, and by the outflows, deaths and

emigration (Sterman, 2002).

The rates of the flows can be impacted by auxiliary variables. These variables enhance model transparency and can help trace causality and understand how different parts of the system influence one another. Causality is modelled through arrows, with a plus-labelled arrow meaning positive causality while a minus-labelled arrow meaning negative causality. For example, access to medical care might have a negative causality on the death outflow in the population stock variable. Shadow variables (labelled in grey in the diagram) represent other variables in the model. They can stand for all types of variables and are simply for aesthetic purposes to reduce model complexity and increase readability (Sterman, 2002).

Although there is more nuance to SD modelling than is described above, these are the only building blocks that will be used in this thesis for modelling. This is mainly due to the fact that the modelling has to be approached from a high level for generalizability of results, since high variability can be found between different value chains in the industry (Sterman, 2002).

## 3.7 Result Verification

For result credibility, multiple steps will be taken. First of all, data triangulation was utilized through interviews, literature, workshops, and site visits. That way, we have many diverse data sources. The findings of this thesis are also explicitly validated through feedback from experts in the field.

## 3.8 Artificial Intelligence (AI) Statement

AI tools were used in the creation of this thesis only for report building. For example, in the context of language correction, grammar improvement, table formatting, and LaTeX reference management. All contributions to this thesis outside of referenced data are our own original work.

# 4

## Results

### 4.1 Research Question 1

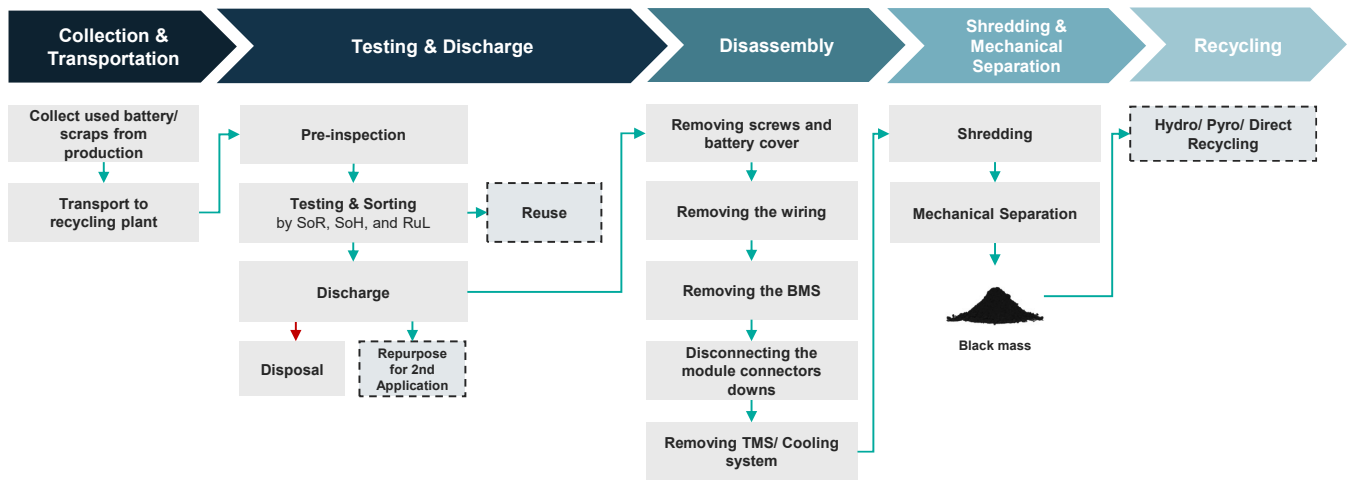
For this question, the task was to analyze the disassembly process and identify the problems that currently plague these processes. The research has revealed that EoL problems are the effects of two causes. The first cause is *product design problems* and the second is *data problems*. Either the product is designed in a way that makes disassembly and recycling difficult or the relevant data is lacking, but in most cases, both are true. The first subsection describes EoL management and different disassembly processes, mainly supported by literature. The following subsections, product design-related problems, data-related problem and consequential problems, are supported by a mixture of literature and interviews.

#### 4.1.1 EoL Management and Disassembly Processes

EoL management of EV batteries is becoming critical in the automotive industry, as improving efficiency of end-of-life management will be the key to addressing both economic and environmental challenges in resource recovery from battery disposal. Usually, the EoL management of batteries for EVs begins when the battery reaches the end of its initial use. However, the primary resource currently comes from battery scraps disposed from production (Gielen et al., 2021). But this is all subjected to change, since the first generation EVs will be reaching their EoL in only a few years. The EoL process has several steps, from collection to transportation, testing and discharge, disassembling, shredding and mechanical separation, and recycling, as illustrated in Fig 4.1

#### Collecting and Transportation

Firstly, the collection and transportation of lithium-ion batteries must be handled safely to avoid potential hazards to human health and the environment. The appropriate regulations and safety protocols must be followed to transport them to



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**Figure 4.1:** EoL Management of EV batteries

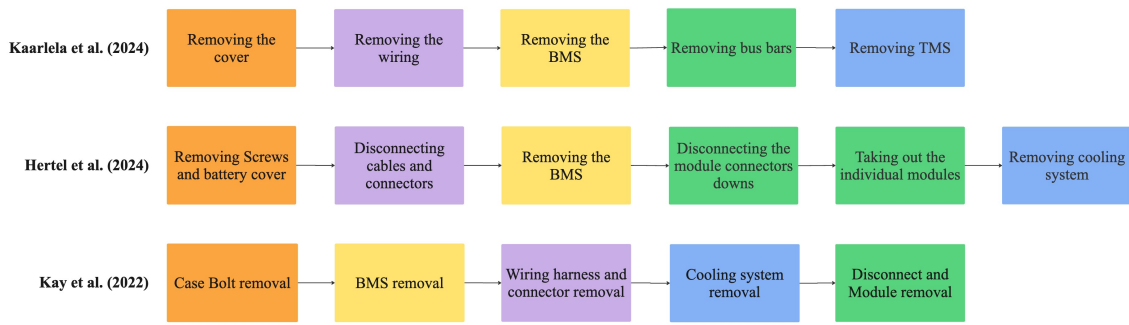
the recycling plants in a secure way (Plotnikov & Schier, 2023). In the EU setting, the used batteries will be collected locally, and they will be transported to regional recycling plants to gain economies of scale [Expert B].

### Testing and Discharging

Once the batteries reach recycling facilities, they undergo the pre-inspection, sorting, and discharge process (Waldmann et al., 2016). Batteries are first stored to ensure safety after transportation, followed by testing to evaluate their condition. The SoR is then evaluated to identify the battery condition (Kaarlela et al., 2024). The damaged or unsafe batteries will not be dismantled, while safe and undamaged batteries will undergo further testing. The state-of-health (SoH) and remaining useful life (RuL) are other indicators for assessing the battery's health and performance (Kaarlela et al., 2024). This data provides information that can help decide practical EoL strategies such as direct recycling, repurposing for a second application, and reuse. Several pieces of information are essential and required at disassembly to enhance process safety. The retired batteries that pass the test will be discharged before they are disassembled.

### Disassembly

In general, the dismantling task of EV batteries from pack to cell level is in general identical regardless of the different designs (Kaarlela et al., 2024). The tasks include removing the cover, removing the wiring, removing the BMS (Batter Management



**Figure 4.2:** Disassembly Steps from Literature Review

System), removing the bus bars, removing the thermal management system (TMS), and removing the modules. However, removing the TMS is optional, as not all EV vehicles are equipped with such a system (Kaarlela et al., 2024).

Moreover, Lander et al. (2023) analyzed the disassembly of six commercial battery packs and presented four main categories: (1) chassis and battery safety, (2) electronic and electrical system components, (3) the dismantling of battery parts, and (4) module separation. As presented in Fig 4.2, the battery dismantling practices of electric vehicles presented by Kaarlela et al. (2024) and Lander et al. (2023) are consistent with the findings of Hertel et al. (2024) and Kay et al. (2022), which present the common procedures for the dismantling of battery packs. Although there are some differences in sequencing and subtasks due to differences in sample vehicles, the core activities are similar.

These common dismantling steps were observed during the site visit to the recycling plant. However, all tasks there were carried out manually, regardless of the type and model of the battery. Additionally, the tools and methods used to approach these steps vary between different battery pack designs.

### Shredding and Mechanical Separation

After disassembly, battery cells are fed into a shredding machine to break them down into small pieces, which allows further mechanical separation of materials. Several separation techniques, including magnetic separation, fine crushing, and sieving, are applied to help separate cathode active powders (Mossali et al., 2020). As a result, this process is very important for recovering the black mass containing critical materials such as lithium, cobalt, and nickel.

During the site visit, it was observed that while the overall process aligns with the paper from Mossali et al. (2020), the operations are carried out under a highly controlled and closed system. This is crucial not only for ensuring the purity

of black mass but also for preventing environmental and social concerns. As the expert highlighted during the visit:

*The dust and residues from the shredding and separation processes could lead to air pollution, so there is a need for enclosed systems in our operations.* [Expert B]

### Recycling

As the demand for electric vehicles continues growing, several advanced recycling technologies have been studied and developed to increase efficiency and reduce environmental impact. According to Harper et al. (2019), Mossali et al. (2020), and Wu et al. (2023), there are three commonly discussed recycling approaches: pyrometallurgy, hydrometallurgy, and direct recycling.

1. **Hydrometallurgy:** A process that uses chemical leaching to extract valuable metals from cathode material.
2. **Pyrometallurgy:** A high-temperature-based process is used to extract an alloy containing Co, Cu, Fe, and Ni.
3. **Direct recycling:** The approach that recovers cathode or anode material from the electrode for refurbishment and reusing in a remanufactured lithium-ion battery.

These three methods differ significantly in terms of technical feasibility, cost-efficiency, and environmental impact, as discussed in the literature. Interestingly, while hydrometallurgy and pyrometallurgy technologies are widely adopted in commercial settings, direct recycling has not been adopted to the same level (Harper et al., 2019; Mossali et al., 2020).

#### 4.1.2 Product Design-related Problems

Disassembling EV batteries presents several challenges for efficient EoL processing and circularity, as presented in Table 4.1. One of the significant obstacles falls into the wide variation of battery pack designs, which differ in structure, weight, and size. Currently, three main types of battery cell shapes are available on the market: cylindrical, prismatic, and pouch (Harper et al., 2019). Furthermore, tools and skilled employees are also required to handle different weights resulting from different design formats (Harper et al., 2019). These significantly prevent the standardization and automation of the EoL practices, especially during the disassembly phase (Ali et al., 2022; Beghi et al., 2023; Harper et al., 2019; Hathaway et al., 2024; Kay et al., 2022; Lander et al., 2023; Zang & Wang, 2022).

Additionally, this complexity is increased by the diverse battery chemistries and materials such as Nickel Manganese Cobalt (NMC), Nickel Cobalt Aluminium (NCA), and other lithium-ion variants as it demands different recycling methods and handling processes (Ali et al., 2022; Beghi et al., 2023; Harper et al., 2019; Hathaway et al., 2024; Mossali et al., 2020; Zang & Wang, 2022).

Using non-detachable joints such as welds and adhesives to strengthen the battery components can further complicate both manual and automated dismantling (Harper et al., 2019; Kay et al., 2022; Lander et al., 2023). This results in labor-intensive, time-consuming processes and higher costs which lower operational efficiency (Beghi et al., 2023; Lander et al., 2023; Tan et al., 2021).

On-site at the battery recycling facility, a number of diverse battery packs from different EV vehicles can be observed. This emphasized that battery designs are far from being consistent and standardized. Moreover, one expert highlights that software and battery chemistry must be considered for proper disassembly, reflecting the complexity of battery pack design and processing:

*The focus should not only be on the hardware, but also on the software and battery chemistries [Expert E]*

In addition, Harper et al. (2019) and [Expert M] also highlighted that many EV batteries are not designed for recyclability. They tend to prioritize powering system optimization, economics and crash safety rather than recyclability, which means that the fundamentals for modularity and ease of disassembling can be overlooked during the design phase. Harper et al. (2019) and Mossali et al. (2020) also called for circular design strategies to facilitate reuse and recycling.

However, designing for circularity is not as straightforward as it may seem. One expert in battery design highlighted the trade-offs involved in battery pack design parameter prioritization:

*Attributes that are really important are durability. And also energy. Or range if you prefer electric range. And also fast charging is an important attribute, so those are the main factors that kind of influence the design, I would say. And we also consider the the recycling and disassembly. But it (DfC) is not the only priority. We also need to fulfil the all this other stuff and cost of course, keeping costs down as well in in manufacturing and the materials and so on. [Expert A]*

A clear example of these trade-offs was provided in one of the interviews. An automotive OEM had the task to select the choice of fastener for the battery pack casing for one of their car models. Although glue is much less preferred when

disassembling the battery pack, it was deemed a necessary design choice to prevent water from getting into the battery pack and to meet safety standards [Expert D].

EV batteries also have a long lifecycle, which means that when they eventually reach their EoL, the battery designed to be optimally disassembled may no longer be optimal, since disassembly/recycling competencies and methods might have changed from when the battery was originally designed [Expert E]. Additionally, some argue that it is difficult to estimate when to set the standard for battery design since battery technologies are still seeing rapid innovations. All of these factors have therefore led DfC to be described as "a moving target", as one interviewee mentions:

*I think the big barrier is that recycling is so complicated. And also always changing and different everywhere. So it's kind of a moving target and I still don't know what we're actually designing for.* [Expert F]

**Table 4.1:** Product design-related problems of EV battery disassembly

Design Problems	Description	Relevant Studies	Respondents
High variability in battery pack design	EV battery packs differ significantly in structure, size, and weight, making standardized disassembly difficult.	(Ali et al., 2022; Beghi et al., 2023; Harper et al., 2019; Hathaway et al., 2024; Kay et al., 2022; Lander et al., 2023; Zang & Wang, 2022)	B, C, E, D
Diverse battery chemistries and materials	Chemistries like NMC and NCA require different processes, increasing recycling complexity.	(Ali et al., 2022; Beghi et al., 2023; Harper et al., 2019; Hathaway et al., 2024; Mossali et al., 2020; Zang & Wang, 2022)	B, C, D
Use of non-detachable joints	Adhesives, welds, and screws make disassembly more difficult. Disassembly is labor-intensive and costly due to fasteners.	(Harper et al., 2019; Kay et al., 2022; Lander et al., 2023) (Beghi et al., 2023; Lander et al., 2023; Tan et al., 2021)	B, C, D, F B
Battery is not designed for circularity	Most batteries lack design features to enable easy, safe, and cost-efficient recycling.	(Harper et al., 2019; Mossali et al., 2020)	A, B, C, D, E

### 4.1.3 Data-related Problems

The level of data exchange gaps between battery design and battery disassembly processes varies significantly between actors in the industry. Different EoL actors have access to information from certain automotive OEMs, while others do not. However, data transparency within the EV battery value chain is generally insufficient, causing several challenges at the battery's EoL stage as shown in Table 4.2.

One major problem is that the BMS, which stores several significant data, is largely inaccessible for actors in the value chain. Among these data, the most important factors related to battery health are SoH and state-of-charge (SoC). These data are very crucial for both EoL decision making and safety assessments. Access to these health conditions is needed to effectively determine whether the battery is suitable for a second life. Batteries with a relatively high SoH (usually >70-80%) are generally assessed as sufficient for a second life in the form of reuse, repurposing, or refurbishing (Berger, Baumgartner, Weinzerl, Bachler, & Schöggel, 2023; Harper et al., 2019; Ott et al., 2024; Pohlmann et al., 2024). As well as, SoC is also required for properly handle the battery before dismantling, as stated by one interviewee:

*We don't have BMS data, so we can't discharge the battery properly, which is causing danger because of leakage of electrolyte. This exposure of toxic gas can stay for some time and it can make all the steel rusty*  
[Expert D]

Battery history data is another critical gap. Information such as whether the battery has been repaired, remanufactured, or involved in an accident, is essential when making decisions about second-life applications (Ott et al., 2024; Pohlmann et al., 2024). Throughout its long life cycle, various factors such as physical damage, deformation, or dirt build-up could affect the battery condition and might cause danger or reduce efficiency when disassembling the battery (Berger et al., 2022).

Another missing key data point is the battery chemistry and material composition. This data is also critical for effective recycling since different recycling methods are best suited to specific chemistries (Berger, Baumgartner, Weinzerl, Bachler, & Schöggel, 2023; Berger et al., 2022; Klohs, Domenic et al., 2023; Ott et al., 2024; Pohlmann et al., 2024). In addition, knowledge regarding the usage of glue and adhesive is essential, as it directly affects dismantling operations in terms of methods and safety [Expert C; Expert M].

For EoL handling, having detailed disassembly instructions is beneficial in reducing the time and effort spent on manual disassembly, which is currently a significant bottleneck in EoL operations. They also potentially reduce the guesswork required from workers who currently have to disassemble them manually [Expert B]. Also, it lowers administration efforts to document the process of each battery type that enters the facility. This information is generally not accessible to EoL actors currently (Berger, Baumgartner, Weinzerl, Bachler, & Schöggel, 2023; Klohs, Domenic et al., 2023; Ott et al., 2024; Pohlmann et al., 2024).

As mentioned above and further highlighted here, battery EoL actors are re-

ceiving battery packs without information regarding their design, SoH, composition, or instructions. This causes significant inefficiencies in battery disassembly. As observed in the site visit, to combat this gap, some actors have begun creating their own internal databases, requiring each battery type to go through analysis and documentation to enhance long-term efficiency [Expert B]. Although this workaround has led to some performance improvement, resource-intensive work still remains, especially given the number of variations of batteries on the market. In fact, even identical car models might not have the same battery pack depending on their year of manufacture [Expert K]. It should be addressed that this is not the case in all scenarios, there are good examples of efficient collaboration in the value chain to optimize the EoL actions, but as one interviewee states, not all actors are interested in such relationships:

*So they are really interested in it. But the others, they don't care, they only care about the money that they will get back from the from the batteries.* [Expert C]

While the information about battery health, chemistry, material components, and disassembly instructions is known to benefit the disassembling process, data sensitivity and intellectual property are barriers to sharing this data across the value chain. (Berger, Rusch, et al., 2023). Stakeholders often believe that sharing this data could result in a loss of competitive advantage and intellectual property (Berger, Baumgartner, Weinzerl, Bachler, & Schöggel, 2023).

The insights from some of the interviews indicate that the material composition and adhesives used are recognized as highly sensitive data on the OEM side. Additionally, recycling processes and technologies are also trade secrets. Thus, secrecy affects the data flow between the OEM and disassembler/recycler in both directions as one interviewee mentions:

*Oh, there is also a barrier like recyclers are kind of secretive because the business case is so tight. So they don't really want to share which machines they use in which order, because that's kind of trade secrets. They don't want other companies to know that just for their competitive advantage.* [Expert F]

In addition, the quality and integrity of data are vital to ensure the proper data-driven decision-making. Currently, the available data is often of poor quality, decreasing the value of the data at the battery EoL (Ott et al., 2024; Pohlmann et al., 2024) [Expert H]. This is especially prevalent in life cycle assessment data and battery diagnostics data (Berger, Baumgartner, Weinzerl, Bachler, & Schöggel,

2023). Furthermore, one interviewee mentions the ambiguity of SoH estimation, and questions if all reporting bodies can be trusted for their estimation:

*So state of health is something that we can debate for hours like, what is the state of health? How should it be computed? It really depends on so many things. So I think there is still a need for SoH estimation algorithm that are independent of what's written in the passport or what's from the BMS and stuff like that. Which, is if car manufacturers, if they are responsible to fill in these battery passports, then you have to trust them I would say, and I don't know if you can trust them. [Expert I]*

**Table 4.2:** Data-related problems of EV battery disassembly

Data Problems	Description	Relevant Studies	Respondents
Lack of battery health data (SoH, SoC)	Critical for assessing second-life potential and ensuring safety during disassembly.	(Berger, Baumgartner, Weinzerl, Bachler, & Schöggl, 2023; Harper et al., 2019; Ott et al., 2024; Pohlmann et al., 2024)	B, C, D, G, I, K, Workshop
Lack of battery history data	Information on repairs, remanufacturing, or accidents is essential for second-life decision-making.	(Ott et al., 2024; Pohlmann et al., 2024)	B, K, Workshop
Lack of chemistry and material data	Required to select suitable recycling methods for optimal material recovery.	(Berger, Baumgartner, Weinzerl, Bachler, & Schöggl, 2023; Berger et al., 2022; Klohs, Domenic et al., 2023; Ott et al., 2024; Pohlmann et al., 2024)	B, C, Workshop
Lack of disassembly instructions	Disassembly instructions help streamline the process and reduce risks and inefficiencies.	(Berger, Baumgartner, Weinzerl, Bachler, & Schöggl, 2023; Klohs, Domenic et al., 2023; Ott et al., 2024; Pohlmann et al., 2024)	B, K, Workshop
High data sensitivity	Data sharing is limited due to IP protection or competitive concerns.	(Berger, Baumgartner, Weinzerl, Bachler, & Schöggl, 2023; Berger, Rusch, et al., 2023)	B, C, E, F
Low data quality	Inaccurate or inconsistent data can lead to poor decisions and safety hazards.	(Berger, Baumgartner, Weinzerl, Bachler, & Schöggl, 2023; Ott et al., 2024; Pohlmann et al., 2024)	C, I, Workshop

#### 4.1.4 Challenges Resulting from Product Design Problems and Data Problems

In this section, both product-related problems and data problems were identified and dissected. The combination of these problems creates various issues in the EoL processes as presented in Table 4.3.

Firstly, safety is one of the most critical concerns in real-world operations of EoL management because of the hazards of lithium-ion batteries. It could stem from

three risks: electrical, fire and explosion, and chemical risks which each of which can interact to trigger one another (Diekmann et al., 2018). Moreover, the potential damage from situations such as car crashes that deform the battery, improper charging, or long-term scratches and wear can also escalate the risk of fire, short circuits, and other dangers. As a result, the lack of reliable data regarding material composition, battery health, and battery conditions can pose severe problems for disassemblers.

Additionally, safety concerns regarding toxic gas exposure and high voltage risk due to improper disassembling practices have also been raised by many scholars (Harper et al., 2019; Kay et al., 2022; Lander et al., 2023). Several industry experts highlight that many current battery designs require brute force to open the battery pack, resulting in a dangerous working environment for disassemblers [Expert B; Expert C; Expert D]. As one of the interviewees stated:

*We've got dedicated teams to disassemble, but everything is important over there to know, because, for example, car makers or battery makers are sometimes using some toxic glue to stick the batteries together, yes. And we need to know what's happening when you're putting for example, some some heat to be able to to disconnect, you know, pieces together. So what's the maximum heat that it expects? Do we need to use special exhaust to make sure that toxic fumes will not affect people who are operating for us? [Expert C]*

The limited possibility for circularity is another issue stemming from both the data and design gaps. The design of batteries that are not designed for circularity, such as module replacement or BMS reprogramming, combined with the unavailability of battery information, can complicate the disassembly process. Furthermore, repairing or refurbishing batteries becomes challenging without accurate estimation of the battery condition. This potentially leads to safety concerns in their second life. (Diekmann et al., 2018; Harper et al., 2019; Kay et al., 2022; Lander et al., 2023). This issue is also emphasized by one recycling expert:

*Batteries are very, very dangerous medium, yes, and people don't understand how big a risk they are exposed to by using second-hand batteries or cells. And I truly believe that there's too much trade of batteries instead of direct treatment of those batteries to recycling plants, yes. There's there's several reasons behind it, yes... but basically the majority of these fires are caused by the fact that people were using batteries for the second time without proper knowledge. [Expert C]*

Furthermore, the usage and the lack of data on battery components and adhesives such as epoxy and glue not only make disassembly difficult but also risk contaminating the black mass, which is the most valuable material recovered during EV battery recycling (Harper et al., 2019) [Expert C]. This is a problem for both recyclers and battery manufacturers, who need to do more work to process the black mass. As stated in Article 8 in the Battery Regulations mentioned above, from 2031 and onwards, there will be a minimal recycled contents requirement for all batteries put to market. This means that increasing the supply of quality black mass is even more critical in the future. One interviewee at EoL facilities explained this topic from their point of view:

*And that the type of battery is contaminating black mass. This is a very, very big problem for us, because obviously when you put these batteries, you shred them, so basically you create different fractions, yes? Out of the fractions, you've got electrolyte, you've got ferrous, non-ferrous, plastic, and black mass... And then such black mass has got a certain value, and this value is based on markets... And depending on purity of the black mass. if the black mass is contaminated nobody wants to take it, and then there is a huge problem because you need to produce more, you know, purify it and and so on. [Expert C]*

Lastly, having inefficient EoL processes can lead to an accumulation of batteries in a queue to receive EoL handling. Given the size and dangers of unhandled waste batteries, storage of these batteries becomes an issue [Expert B]. This waiting time is a typical case of waste in the EoL process from the perspective of queuing theory and lean management. That is because while waiting, the batteries do not provide any value, only accumulate storage costs (Six Sigma, n.d.).

## 4. Results

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**Table 4.3:** Challenges resulting from product design problems and data problems

Challenges	Description	Relevant Studies	Respondents
Safety concerns	High voltage, toxic chemicals, and risk of fire make handling dangerous. Batteries come in various conditions.	(Diekmann et al., 2018; Harper et al., 2019; Kay et al., 2022; Lander et al., 2023)	B, C, D
Limited circularity potential	Designs that do not enable circular operations, along with lacking key data decrease the potential of second life and efficient recycling	(Berger, Baumgartner, Weinzerl, Bachler, & Schöggel, 2023; Harper et al., 2019; Kim et al., 2023; Klohs, Domenic et al., 2023; Pohlmann et al., 2024)	B, C, D
Black mass contamination due to adhesive usage	Adhesives and other substances can contaminate black mass, reducing its value and recyclability.	(Harper et al., 2019)	C, D
Queue accumulation and long waiting times	Due to inefficient EoL processes, unhandled waste batteries can accumulate at EoL facilities. This requires space and resources for no value added to EoL operations.	–	B

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## 4.2 Research Question 2

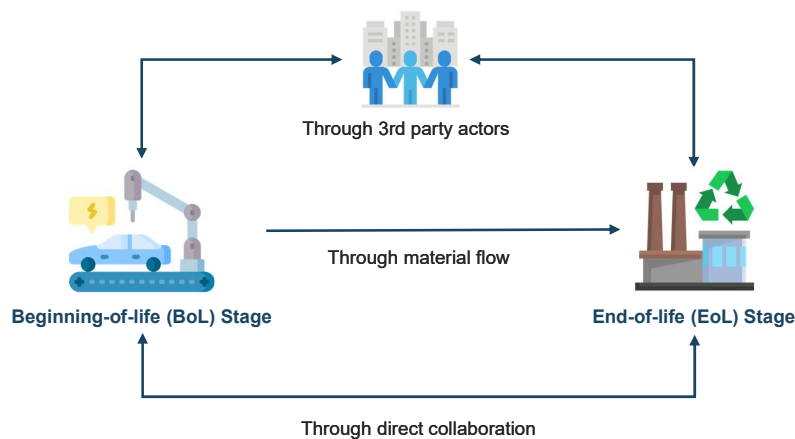
The goal of this question was to identify and analyze tools and mechanisms that could enhance data exchange within the value chain. To answer this question, the flow of information between the BoL and EoL stages is established, then key tools and mechanisms are explored and ultimately analyzed. The source of information was gathered both from literature and expert interviews.

### 4.2.1 Information Flow between BoL and EoL Stages

As has been established earlier in this thesis, data exchange and communication between the two stages are far from optimal. That does not mean that these exchanges do not exist currently. In the past few years, as the industry has matured, data exchange has seen some improvements, with even more scheduled in the next years.

Information flow refers to the information exchange between actors in the supply chain (Badenhorst-Weiss et al., 2013). As discussed by Berger, Baumgartner, Weinzerl, Bachler, and Schöggel (2023), Pohlmann et al. (2024) and [Expert K], insufficient data exchange and data exchange systems are some of the biggest barriers in implementing circularity in value chains. It is therefore vital to have developed sufficient information flows when implementing circular thinking and models within the value chain.

From the literature and interviews, three categories of information flows were identified. A visual representation of these flows can be seen in Figure 4.3. They are exchanges through material flow, through 3rd party organizations and through direct collaborations.



**Figure 4.3:** Visual Representation of Information Flows Identified in the Thesis

### 4.2.2 Data Exchange Through Material Flow - The DPP

Data exchange through material flow refers to information that is exchanged as materials are received. This flow is a one-directional flow from BoL stages to EoL. The material in this context refers to the batteries themselves, as BoL actors include information on the battery itself, which is then accessible to the EoL actors when they ultimately receive the battery at the EoL stages. The only tool and mechanism that was identified in this thesis, categorized as a mechanism of data exchange through material flow, was the DPP.

The DPP is a digital tool introduced to enable greater transparency of the value chain and data exchange for better product management (Berger et al., 2022). As of February 2027, the passport will be required to be accessible via a QR code on the battery itself for every EV battery placed on the market (European Parliament and Council of the European Union, 2023).

The DPP can be useful in several use cases. For example, in regulatory context, it assists governing bodies in monitoring the compliance of the standards and regulations in place. But more importantly for the context of this thesis, it enables information exchange through material throughout the value chain down to the EoL stages where data is currently sorely lacking (Berger et al., 2022).

The passport will contain two types of data, static and dynamic. The static data are data points that, once determined, never change during the lifecycle of the battery. This information is referred to as supply chain data, and discloses what was done at each stage to bring the battery to market. Dynamic data, or use-phase data, refers to data that changes as time passes. These data points are, for example, the SoC and SoH of the battery (Battery Pass Consortium, 2023). The directly quoted data requirements for the DPP are addressed in Annex XIII of the Battery Regulation, and as can be observed in Table 4.4, all missing data identified in RQ1 is covered in the regulation. This would provide great value to EoL actors, as one recycler mentions:

*So basically, if you if you receive a battery and you would, for example, have a digital battery passport to scan and to see the chemical structure of it, then you could go through the appropriate measures to basically mitigate this [Lack of chemistry and material data] problem, that you have in here. [Expert C]*

It also addresses the quality and sensitivity problems acknowledged in RQ1. Table 4.5 showcases how it aims to do so.

**Table 4.4:** Mapping of identified missing data problems to Battery Regulation requirements (Annex XIII) (European Parliament and Council of the European Union, 2023)

EoL Problem	DPP data requirements	Annex XIII reference
Lack of battery health data (SoH, SoC)	<i>The values for performance and durability parameters referred to in Article 10(1), when the battery is placed on the market and when it is subject to changes in its status</i>	Point 4(a)
	<i>Information on the state of health of the battery pursuant to Article 14</i>	Point 4(b)
Lack of battery history data	<i>Information on the status of the battery, defined as original, repurposed, re-used, re-manufactured or waste</i>	Point 4(c)
Lack of chemistry and material data	<i>The material composition of the battery, including its chemistry, hazardous substances present in the battery, other than mercury, cadmium or lead, and critical raw materials present in the battery</i>	Point 1(b)
	<i>Detailed composition, including materials used in the cathode, anode and electrolyte</i>	Point 2(a)
Lack of disassembly instructions	<i>Dismantling information, including at least: exploded diagrams of the battery system/pack showing the location of battery cells, disassembly sequences, type and number of fastening techniques to be unlocked, tools required for disassembly, warnings if risk of damaging parts exist, amount of cells used and layout</i>	Point 2(c)

**Table 4.5:** Mapping of identified data sensitivity and quality problems to Battery Regulation requirements (Article 77 & 78) (European Parliament and Council of the European Union, 2023)

Data Problem	DPP data requirements	Battery Regulation reference
High data sensitivity	Data sensitivity is addressed through through tiered access levels to data required by Annex XIII:	
	<b>Point 1:</b> Accessible to the public	Art. 77 Para. 2(a)
	<b>Point 2 &amp; 4:</b> Accessible only to persons with a legitimate interest and the Commission	Art. 77 Para. 2(b)
	<b>Point 3:</b> Restricted to authorities and notified bodies	Art. 77 Para. 2(c)
Low data quality	<i>The economic operator placing the battery on the market shall ensure that the information in the battery passport is accurate, complete and up to date. It may give written authorisation to any other operator to act on its behalf.</i>	Art. 77 Para. 4
	<i>All information included in the battery passport shall be based on open standards and be in an interoperable format, transferable through an open interoperable data exchange network without vendor lock-in, machine-readable, structured and searchable, in accordance with the essential requirements laid down in Article 78.</i>	Art. 77 Para. 5
	<i>Data authentication, reliability and integrity shall be ensured</i>	Art. 78 Point (a)

The technical implementation of the DPP is still uncertain. Although some technical conditions have to be met in accordance to the regulation, the way in which the passport will be built, stored and maintained is still unclear. As Table 4.5 highlights as an example: *Data authentication, reliability and integrity shall be ensured*, but nowhere is it explicitly determined how to fulfill these conditions. One of these uncertainties is regarding how the passport collects data and where it is stored. Butera and Gatteschi (2024) discuss how blockchain could play a role in the implementation of the DPP, as it fulfills many of the technical requirements discussed in the Battery Regulations, such as the data system should be decentral-

ized and highly secure. Still, there are drawbacks of using blockchain technology for storing this data, with one of the main drawbacks being the high costs of storing large amount of data. Berger, Rusch, et al. (2023) propose ML models as a way of preserving data confidentiality while enabling better EoL decision making. The economic operator of the battery would therefore develop their own battery assessment ML models and either offer relevant actors access to the model itself to use for battery assessments or share the outputs of their model for each battery instance to these actors, with the outputs stored within the DPP. EoL actors would therefore not be able to access raw battery data, only computed values needed for EoL decision making. Rusch et al. (2023) discuss how different technologies, such as Internet of Thing (IoT), AI, big data and blockchain, can support better data collection and storing for the DPP for enhanced lifecycle management and EoL decision making. There are therefore still many uncertainties in the technical implementation of the passport and high demands for security and infrastructure.

These uncertainties and high requirements become even more challenging when considering that the implementation deadline, February 2027, is approaching fast [Expert A, Expert J, Expert O]. A representative of an OEM expressed these concerns although remaining positive for the future of the technology:

*I see it this way, this legislation is new for all OEMs and battery producers. As with any new requirement, the initial phase is challenging: gathering necessary data points, standardize formats, consolidating information, and automating this. But looking ahead, there will be systems in place to manage this seamlessly. So yes, it might be challenging now, but its not a hurdle we wont overcome as an industry. [Expert J]*

### 4.2.3 Data Exchange Through Third-Party Organization

Data exchange through third third-party organizations refers to the bidirectional flow between BoL and EoL actors, where the information goes through a third-party organization.

#### Design Guidelines and Standards

As discussed earlier in the thesis, variability in battery designs and EoL processes mean that standardization is a difficult task. DfC is a "moving target" [Expert F]. To bridge this gap, some have proposed using other more mature industries as examples and setting certain design standards within the industry. One of these industries is the electronics industry. As one interviewee stated:

*And so, for example, a design guideline could be in the plastic of the product, you add, like some features, so that it will release the parts more easily while being in a shredder. So you derive some design guidelines from what you know of the recycling process. [Expert G]*

Design guidelines and standards may therefore assist battery designers in designing batteries for optimal EoL performance while still satisfying their performance requirements. They do need input from both sides of the supply chain, BoL and EoL stages, to be effective. A guideline that is not in line with EoL methods and technologies provides no value, and the same goes for a guideline that does not consider performance parameters for battery design. It is therefore important for some actor to gather the requirements from both sides and find the optimal solution that satisfies the requirements of both parties. This is currently being worked on in Sweden, with results estimated in late 2026 [Expert D].

There are still some weaknesses and challenges in such mechanisms. One of which is the difficult creation and maintenance of the guidelines and standards. Different EoL actors have different tools, technologies, competencies and processes. This means that a design could be optimal for one specific disassembler/recycler but not for another [Expert E]. Also, as established earlier, circularity is a moving target. Technologies and methods can change at both BoL and EoL stages, so they require constant re-evaluations. Introducing a standard or a certain guideline too early can also pose a risk. It could inhibit the growth potential of the technologies and cause them to stagnate if the standards are determined while product innovation in the industry is still high (Hicks & Goronzy, 1966).

### **Data Platforms**

Data platforms refer to an online platform hosted by a third party in which battery designers and EoL actors can connect through and exchange data. Siska et al. (2023) discussed the concept of data spaces in this context. A data space is a decentralized data ecosystem that serves as a platform for secure data exchange between the provider and consumer of data. Accessibility to the data is regulated by rules and contracts, and data providers can provide access to certain datasets with the appropriate contracts. This concept could, therefore, enable collaboration and increase trust and safety of the data sharing.

Another conceptualization of these data platforms is in standardized data sheets. By standardizing the product data, it provides a basis for further standardization since it ensures consistency and comparability between different product lines. Alongside the fact that it enables circular designs since circularity is more

easily measurable in the standardized data architecture. As one data platform solutions actor mentioned:

*So when we talk about circularity, it comes with different challenges, and really our essence is to say that a product without data is waste. ... You need the right level of information to take proper action. ... [Data platform] is a template that allows you to easily record the circular properties of your product... always from the manufacturer point of view, how did I design my product from a circular point of view? [Expert H]*

The battery designers can then provide access to certain data points to EoL actors through the platform, therefore bridging the gap between the two to some extent. Regarding how this could mitigate problems at the EoL the same interviewee stated:

*For an end-of-life standpoint, yes, there are several things which could be of interest in the [Data platform]. First, it provides information on the content of the product, like if there are toxic products or products of concern... The other thing is that for end-of-life, its also providing information on the end-of-life options whether you can recycle, compost, refurbish so a recycler can know whether the product has some end-of-life features and to what extent. [Expert H]*

These are just two cases from many available in the current industry landscape. One possible threat to this mechanism is the reliance of OEMs on a third-party. As Berger, Rusch, et al. (2023) highlights, the need for confidentiality and data security is very high for this type of data sharing. This means that OEMs might be skeptical in trusting a third-party actor in the current industry landscape, given the sensitivity of the information handled (KPMG LLP, 2024).

#### 4.2.4 Data Exchange Through Direct Collaborations

The last category of information flow is data exchange through direct collaborations. This contains all information delivered directly between the two stages as part of direct collaboration and communication.

##### Design Consulting

Design consulting refers to the direct consulting work of EoL actors in assisting in battery design processes. By involving EoL actors in the battery design processes, the designers can optimize the battery, utilizing knowledge and experience from EoL

actors to maximize circularity of their designs [Expert G]. This is currently being done to some degree in the current industry [Expert B; Expert C]. One EoL actor describes this mechanism as such:

*Yes, so we can say that we've got strategic partners that are enabling us even to be at their engineering centers, there. So we are flying over to the factories. We can see how the the battery is being made and we can we can tell them that, okay, this and that in recycling perspective could be changed. [Expert C]*

This can increase R&D costs, as Roy and Potter (1990) discuss, since it requires more time and effort from more people in the design process. That alone can disincentivize these actions, especially when costs are of high importance [Workshop]. Also, since batteries have such a long lifecycle (Volvo Energy, 2023), the consultation might no longer be accurate in the future when the battery reaches its EoL, which could threaten the validity of the consultation itself. One limitation of this mechanism is generalization of consultation results, since EoL methods and technologies can be very different in different areas. So consultations from a single EoL facility might not be as applicable for other facilities. This could also risk sensitive data leaks, since external actors are gaining access to a secretive process. One OEM representative mentioned this in one interview:

*There are, of course many, many of them out there, but we try to share. It could be a bit secret if it's an early design, it's harder for us to share fully because it's not yet in the market and it could be competitors interested in that and so on. [Expert A]*

### **Design Testing**

Another way of approaching direct collaboration is through design testing. In these arrangements, new designs/prototypes are sent to EoL facilities to test how the product performs during disassembly and recycling. From this testing, the designers also gain knowledge regarding how the EoL actors operate in order to better account for them in their future designs [Expert G]. This sort of arrangement can already be seen to some extent in the industry, with one OEM representative stating:

*And we actually talk quite a lot to them. We have research programmes and actually when we have early prototypes, we have collaboration. So we send batteries, we send some batteries to [Recycling Company] for instance, and also [Recycling Company] so that they can explore and we*

*get feedback from them back into the design teams.* [Expert A]

The issue of increased R&D costs along with uncertainty of future EoL technologies and risks of data sharing also could be problematic for this mechanism like for design consulting.

### **Direct Sharing**

Direct sharing refers to the mechanism of direct data sharing between battery designers and EoL actors. This can be in the form of providing access directly into a subset of either databases (for example, providing direct access to battery design drawings/EoL processes [Expert A]), or in the form of direct communication. One of the EoL organizations that was interviewed described the nature of their direct sharing collaboration with an OEM:

*So [Automotive OEM], or whoever it is, yes, they need to provide us full manual instructions for the sample and for content the instruction, content specification data sheet that is allowing us to build the process. Yes, since this process needs to be approved by themselves. They are coming over for audits. So it's not happening like this that they're just sending and that's it. They are auditing the factory, they're providing direct exchange of information.* [Expert C]

This mechanism might also require some investments in information technology to create a safe sharing platform, given the sensitivity of the information (Berger, Rusch, et al., 2023). This method is also subject to the risk of data leaks as for previous mechanisms.

### **Performance Reporting**

Another mechanism of direct collaboration is in the form of performance reporting. As mentioned earlier, some EoL actors have resorted to creating internal databases given the lack of battery design data they get beforehand. This data can then be shared back to the OEM in which the battery belonged to in the form of performance reporting. This reporting can contain details such as which design choices made disassembly difficult and which ones enable more efficient EoL handling. This is currently being done to some extent in the industry [Expert B; Expert C], but in an informal manner. This mechanism is also victim to the long lifecycles of batteries, since most reporting will be on battery designs that were implemented years before they were recycled.

### **4.2.5 Evaluation of Tools and Mechanisms Through SWOT Analysis**

To summarize the identified tools and mechanisms, and analyze their upsides and downsides, the SWOT framework was utilized for the presentation. The SWOT can be observed in Table 4.6.

**Table 4.6:** SWOT Analysis of Identified Tools and Mechanisms for Data Exchange in the EV Battery Value Chain

<b>Tool / Mechanism</b>	<b>Strengths</b>	<b>Weaknesses</b>	<b>Opportunities</b>	<b>Threats</b>
<b>Digital Product Passport (DPP)</b>	<ul style="list-style-type: none"> <li>- Regulatory backing</li> <li>- Addresses data gaps</li> <li>- Value to many stakeholders</li> </ul>	<ul style="list-style-type: none"> <li>- High implementation uncertainties</li> <li>- High technical and security requirements</li> </ul>	<ul style="list-style-type: none"> <li>- Enables compliance monitoring</li> <li>- Enables circularity and enhanced EoL decision making</li> </ul>	<ul style="list-style-type: none"> <li>- Approaching deadline</li> <li>- Concept still underdeveloped</li> <li>- Data/IP protection concerns</li> </ul>
<b>Design Guidelines and Standards</b>	<ul style="list-style-type: none"> <li>- Aligns BoL and EoL needs</li> <li>- Reduces design variations</li> <li>- Seen success in other industries</li> </ul>	<ul style="list-style-type: none"> <li>- Difficult to generalize</li> <li>- High maintenance due to changing operational environments</li> </ul>	<ul style="list-style-type: none"> <li>- Bridges the knowledge gap of good vs bad design choices</li> <li>- Basis for benchmarking</li> </ul>	<ul style="list-style-type: none"> <li>- Lack of interest of unincentivized designers</li> <li>- Risk of technological stagnation due to preemptive standardation</li> </ul>
<b>Data Platforms</b>	<ul style="list-style-type: none"> <li>- Variety of platform possibilities</li> <li>- Access control to data</li> <li>- Standardized data architecture</li> </ul>	<ul style="list-style-type: none"> <li>- High technicality and security requirements</li> </ul>	<ul style="list-style-type: none"> <li>- No established platform, opportunities for new players to enter</li> <li>- Could set a industry-wide data standard</li> <li>- Enables safe data sharing</li> </ul>	<ul style="list-style-type: none"> <li>- Uncertain demand for platforms</li> <li>- Cybersecurity risks</li> <li>- Third-party operated which could spook actors</li> </ul>
<b>Design Consulting</b>	<ul style="list-style-type: none"> <li>- Ensures circularity of battery design</li> </ul>	<ul style="list-style-type: none"> <li>- Increased resource requirement for R&amp;D</li> <li>- Only applicable to a single EoL actor</li> </ul>	<ul style="list-style-type: none"> <li>- Promotes circular designs</li> <li>- Strengthens relationships</li> </ul>	<ul style="list-style-type: none"> <li>- Data leak risks</li> <li>- Long lifecycles means that designs are outdated when battery reaches EoL</li> </ul>
<b>Design Testing</b>	<ul style="list-style-type: none"> <li>- Validates recyclability early</li> <li>- Instant data feedback loops</li> </ul>	<ul style="list-style-type: none"> <li>- Increased resource requirement for R&amp;D</li> <li>- Only applicable for single EoL actor</li> </ul>	<ul style="list-style-type: none"> <li>- Strengthens relationships and increases alignment</li> </ul>	<ul style="list-style-type: none"> <li>- Data leak risks</li> <li>- Long lifecycles means that designs are outdated when battery reaches EoL</li> </ul>
<b>Direct Data Sharing</b>	<ul style="list-style-type: none"> <li>- Access to necessary data and information</li> <li>- Not dependant on a third party</li> </ul>	<ul style="list-style-type: none"> <li>- Investment requirements</li> </ul>	<ul style="list-style-type: none"> <li>- Foundation for APIs and digital sharing models</li> </ul>	<ul style="list-style-type: none"> <li>- IP risks</li> <li>- No incentives for data sharing</li> </ul>
<b>Performance Reporting</b>	<ul style="list-style-type: none"> <li>- Creates information feedback loops</li> </ul>	<ul style="list-style-type: none"> <li>- Often informal</li> </ul>	<ul style="list-style-type: none"> <li>- Enables informed design decision making</li> </ul>	<ul style="list-style-type: none"> <li>- Reporting on old designs, due to long product lifecycles</li> </ul>

### 4.3 Research Question 3

This research question attempts to address the apparent lack of incentives for data transparency and circular product design of EV batteries. As discussed in several interviews, current linear models do not offer any incentives for OEMs participating in such collaborations and data exchange, since they do not see any economic value in sharing sensitive data and including circular principles in their operations [Expert C, Expert F, Expert G]. As discussed earlier, the Battery Regulation forces OEMs to take some actions to increase industry circularity. But in this question, the goal was to discuss scenarios in which circularity becomes a pivotal part of the OEM's competitive advantage instead of being a regulatory requirement to fulfill.

Since there is great variability in value chain structures, regional differences and applicability, the proposed solution was crafted at a high level for increased generalizability. Additionally, a single business model was picked for further analysis, although other valid models do fit the criteria of incentivizing the factors above, due to feasibility constraints. The business model chosen is Battery-as-a-Service (BaaS). The reasoning of this choice is based on the opinions of several industry experts on what they believe has the biggest potential towards circularity [Expert E; Expert G; Expert L; Expert N].

#### 4.3.1 BaaS Business Model

As mentioned in RQ1 and RQ2, a lack of incentives to share data is a critical challenge throughout the battery value chain. In particular, the data sharing between EoL actors such as disassemblers, recyclers, and OEMs is a critical barrier to achieving a CE. To tackle this problem, improvement of systematic disassembling should be integrated into the broader closed-loop supply chain (CLSP) (Glöser-Chahoud et al., 2021). Additionally, when combined with the higher level of the CE concept, including rethink, redesign, and reduce, innovative business models and product-service-systems (PSS), it can provide provide incentives for collaboration (Glöser-Chahoud et al., 2021). Tukker (2004) also highlights that the most promising forms of business models from a sustainability perspective involve product renting, sharing, pooling, and functional PSSs.

According to Boehm and Thomas (2013), PSS refers to an integrated bundle of tangible products and intangible services to increase value and enhance customer utility. Although after-sales services have been present in the automotive industry since 1980, the concept of "anything as a service" has only gained serious traction in the 2020s (Vandermerwe & Erixon, 2023). This shift towards service-based models

was also observed in the interviews. As one expert in circular economy mentioned:

*I'm not a data expert, but in general, I think this incentivizes collaboration. We once had a project. It was in mechanical engineering so it didn't have anything to do with batteries, but I think that the approach can be transferred to other products and so on. Because I mean, in general, I think, in a circular economy, we'll be shifting towards service models.* [Expert L]

The BaaS business model is a potential illustration of a PSS. Unlike in a traditional product-oriented system, the battery is no longer owned by the car owner, instead, ownership shifts to the provider, who in this case is usually OEMs. This model allows OEMs to offer battery usage through a subscription or pay-per-use model (Tukker, 2004), for example a pay-per-km or pay-per-kWh model. A well-known application of this model is seen in the Chinese company NIO, which even offer battery swapping as a part of their value proposition. The company has officially launched BaaS to the market in 2020. With this model, the company provides comprehensive services, including vehicle-battery separation, battery subscription, and chargeable, swappable, and upgradable batteries (NIO, 2020).

In addition to the battery ownership, the BaaS model allows OEMs as a battery/service provider to retain control over battery-related data. This authority allows OEMs to access reliable battery performance, facilitating informed decision-making in CE strategies (Ahuja et al., 2020; Chirumalla et al., 2024) [Expert K]. On the one hand, involvement in EoL management can incentivize OEMs to share useful data with EoL actors to increase the value of their batteries. On the other hand, EoL actors can give feedback about dismantling difficulties or material recovery. This collaboration can support OEMs in redesigning batteries to be more circular (Tukker, 2015), for example, by improving modularity, reducing adhesives, or making components easier to sort and reuse.

To visualize the concept of BaaS, the Circular Business Model Canvas by Lewandowski (2016) is used as presented in Table 4.7. There are 11 elements of business aspects to be considered as follows:

### **Value Proposition**

With BaaS, particularly under battery leasing, customers can own an EV without bearing the high upfront cost of the battery, which typically accounts for 30-40% of the vehicles total price (Jiao & Evans, 2018; KPMG International, 2023).

This can potentially lower the financial barrier to EV adoption (Shi & Hu,

2024) and consumers' economic perceptions to purchase EVs (Ahuja et al., 2020). Furthermore, the function of a battery, such as capacity and usage, can be tailored based on customer needs, which increases customers' perceived value and utility (Mont & Tukker, 2006).

### **Customer Segments**

The lower initial investment in adopting electric vehicles could expand to cost-conscious customer segments, in addition to individual car owners and fleet operators of electric vehicles. These can be owners of commercial and residential buildings and small companies (Altuntas Vural et al., 2024). Additionally, since OEMs have complete control of the battery, the used batteries can be sold or leased to another business segment for other applications, such as stationary energy storage (Altuntas Vural et al., 2024).

### **Customer Relationships**

Since the OEM retains ownership of the battery in possession of the customer, the relationship is closer with the customer. This enables recurring interactions and retention while maintaining the batteries in good condition over its lifecycle (Jiao & Evans, 2016; Toorajipour et al., 2024). In general, service models can offer customized services based on customer needs which increase customer loyalty (Tukker, 2004). S

### **Channels**

The main physical channel is service stations. However, with the rise of digitalisation facilitated by several digital technologies, the channels are shifting towards the internet (Lewandowski, 2016). Thus, applications or online platforms can also be another significant channel in delivering the value proposition.

### **Key Partners**

BaaS requires the collaboration of various stakeholders in the ecosystem. OEMs can drive this change by partnering with significant stakeholders in this closed-loop supply chain, including recyclers, dismantlers, and logistics providers (Altuntas Vural et al., 2024). This collaboration may increase trust and maintain a long-term relationship between stakeholders (Laubscher & Marinelli, 2014).

### **Key Resources**

Service points are essential outposts when offering BaaS, while the digital platform also plays a vital role in supporting the ecosystem. A real-time tracking system that monitors battery health, usage, and location requires various technologies. These digital technologies can be applied for predictive maintenance and usage optimization (Rusch et al., 2023). The data infrastructure should also support the DPPs by ensuring data security and enabling data sharing across the battery value chain.

### **Key Activities**

For effective value capture of the leased batteries, the OEMs must manage the reverse supply logistic operations, along with effective and efficient EoL processes (Jiao & Evans, 2018; Toorajipour et al., 2024). The company can offer bundled services, including leasing and other battery-related services. The option of battery swapping has also demonstrated potential. However, in order to provide these, a well-managed digital and physical infrastructure must be developed.

### **Cost Structures**

This model requires upfront investment in infrastructures. First, building service stations that support key activities such as maintenance and even battery swapping. Second, the well-organized logistics network for collecting the battery adds additional costs, especially considering reverse logistics and safety standards. Lastly, developing robust data infrastructure to enhance operational efficiency and data transparency (Jiao & Evans, 2016; Toorajipour et al., 2024).

### **Revenue Streams**

Revenue streams directly depend on the value proposition. In general, the revenue of BaaS comes from service-based use rather than selling volumes of products (Laubscher & Marinelli, 2014). This enables OEMs to not only compete on price but rather to extract value throughout the battery lifecycle (Jiao & Evans, 2018). Lewandowski (2016) defined four common revenue structures as follows:

1. Input-based PSS: Users pay per product or per service.
2. Availability-based PSS: This follows a subscription model.
3. Usage-based PSS: this requires a one-time payment per use to access to product and service.
4. Performance-based PSS: This focuses on outcomes such as performance-based contracting.

### **Take Back Systems**

To achieve a CE, the take-back system plays an important role in looping the material into the value chain (Ellen MacArthur Foundation, n.d.). OEMs can take the battery back by connecting reverse logistics operations with service points where batteries are automatically returned for inspection. This also supports responsible EoL management and enables circular flows.

### **Adoption factors**

The factors influencing the adoption of business models depend on organizational capabilities and external factors (Lewandowski, 2016). More importantly, Jeppe et al. (2023) emphasize that policy and external factors play an important role in the batteries and recycling industry. The EV battery industry transition requires strong regulatory frameworks and incentivizing business models (Ahuja et al., 2020). This factor is also discussed by Altuntas Vural et al. (2024) that unclear and misaligned regulations regarding the producer's responsibility for the battery transferred to the vehicle owner after EV sales can disincentivize OEMs from initiating the BaaS model. Thus, regulations must be developed to facilitate service-based ownership models like BaaS.

Operating a service-based business model requires new competencies for OEMs to adopt service centric culture and develop organizational structure that support service growth (Kowalkowski & Ulaga, 2017). In other words, instead of focusing solely on selling products, they need to develop skills for providing services. Additionally, because this business model involves complex activities, collaboration among stakeholders is essential to facilitate resource sharing and maximize long-term value (Altuntas Vural et al., 2024).

**Table 4.7:** Circular Business Model Canvas of Battery-as-a-Service (BaaS)

Canvas Element	Description
<b>Value Proposition</b>	Lower EV upfront cost by separating battery ownership; increase customer satisfaction by offering tailored battery services
<b>Customer Segments</b>	Lower EV investment could attract cost-conscious segments beyond traditional users and expand the potential segment to small businesses and secondary applications.
<b>Customer Relationships</b>	Offering customized services build long-term relationships with customers.
<b>Channels</b>	Service stations for battery swapping/maintenance; digital platforms or apps.
<b>Key Partners</b>	Recyclers, logistics providers, and data platform partners to enable battery lifecycle services and data sharing.
<b>Key Resources</b>	Service station; IoT-enabled technologies; digital infrastructure.
<b>Key Activities</b>	Battery leasing, swapping, upgrading, and maintenance; managing digital platforms and enabling data feedback loops across the value chain.
<b>Cost Structure</b>	Investment in: (1) infrastructure for service stations, (2) reverse logistics for battery return and safety, (3) digital infrastructure for monitoring and data flow.
<b>Revenue Streams</b>	Service-based models, including Input-based (pay-per-service), Availability-based (subscriptions), Usage-based (pay-per-use), and performance-based (performance-based contracts).
<b>Take Back System</b>	Batteries returned via service stations and reverse logistic system.
<b>Adoption Factors</b>	Enhance organizational capabilities and consider external factors, especially the support provided by the regulatory framework.

### 4.3.2 BaaS to Incentivize Data Transparency and Circular Designs

Although relatively immature for individual automotives, the service-based model has seen success in the truck industry. When asked how big of a role service has in their business model compared to traditional sales the truck OEM interviewee stated: *"I would say service would be the bigger part of our business. But we're not going to say no if someone wants to buy our trucks [Expert O].* The expert furthermore emphasizes the role of information transparency and collaboration in these service based systems:

*Of course, when we talk about service models, they (collaborations and information exchanges) become even more. For example, requesting, such as when we should change our batteries? Is 80% of the battery life or should we change or what the number is... And the conditions in which the batteries of the vehicles are being used. So we need a lot of information, continuous information, in order to make better decisions on things. So yes, it requires a lot of data sharing and to our customer*

*companies in order to take care of the trucks.* [Expert O]

To further highlight how BaaS can incentivize data transparency and circular designs of batteries, a system dynamics model was constructed. The model can be observed in Figure 4.4. This simple demonstrative model is scoped down to the value drivers from the perspective of the OEM regarding EV batteries and how the battery lifecycle affects them. The goal of the model is to showcase how BaaS enables circular design and data transparency to potentially increase profitability. The model is built on the results previously gathered from this thesis.

The main stock variable that needs to increase is the *OEM profits* stock variable. There are two revenue inflows included in the model and two cost outflows. The two revenue streams included in the model are *Vehicle sales revenue* and *Battery leasing revenue*. In the simplified model, revenue from vehicle sales is a direct result of the demand of each vehicle and the pricing of the vehicle. *EV Demand* is modeled as a result of *External demand influencers*, such as regulatory pressures and other variables outside of the model scope, and *Vehicle pricing*, since more customers could afford such vehicles with a lower upfront cost. As previously mentioned, by unbundling the battery from the vehicle and offering it as a service, the BaaS model lowers the initial purchase price of the EV. This could increase demand significantly. This could lead to higher unit sales but as unit price lowers it has a balancing effect on the revenue stream itself. But more crucially, it would create a larger number of batteries in use.

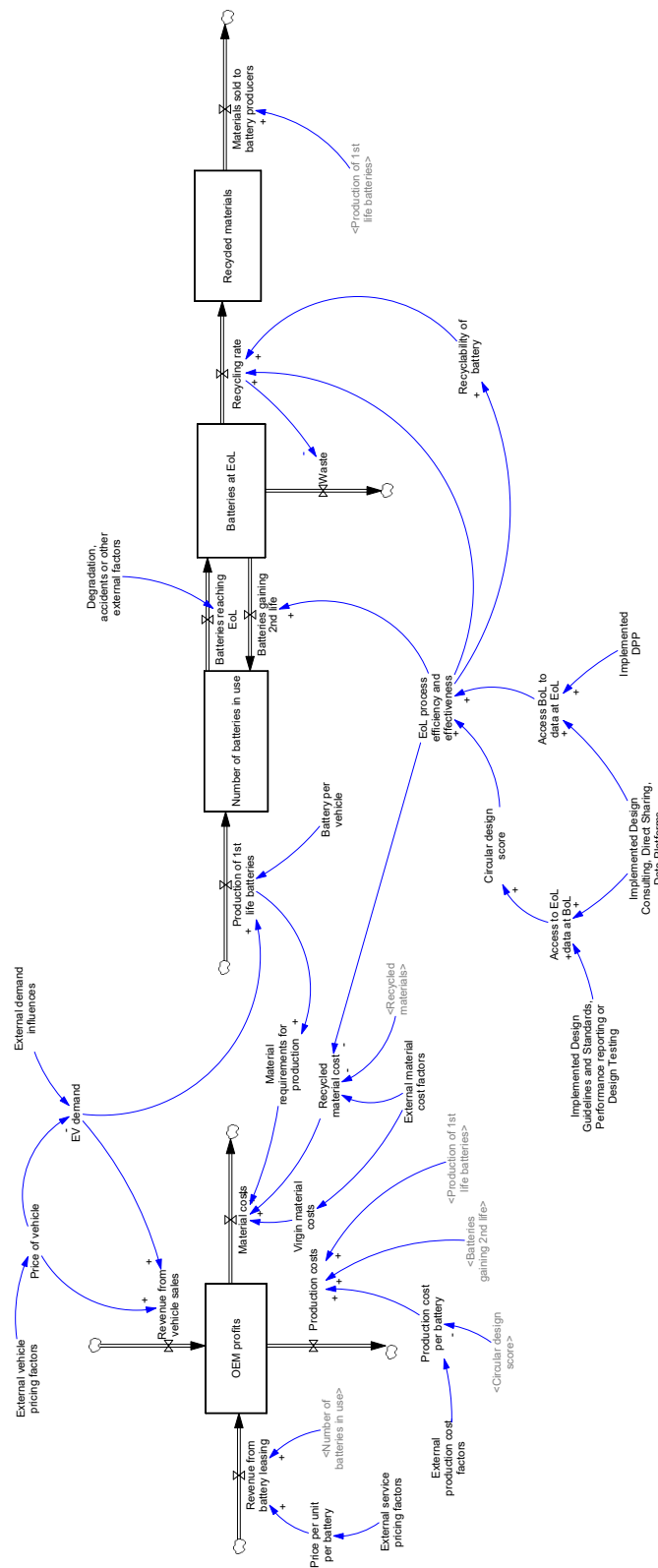
*Number of batteries in use* is a key variable that impacts the revenue from battery leasing, along with the pricing per unit per battery. That means that maximizing the number of batteries in use is incentivized for the OEM. Batteries stay in use, bringing in revenue, until the battery reaches its end of first life. This can happen due to a variety of reasons outside the scope of this model, aggregated in the variable *Degradation, accidents or other external factors*. When a battery reaches its EoL it does not provide value to the OEM. Therefore, it is incentivized to bring batteries at EoL to their second life as fast and economically efficient as possible to regain value from their asset. If the battery is not suitable for a second life, the OEM would want it to be recycled as efficiently as possible to swiftly reclaim the materials of their asset for future battery production. To enable either one of these paths, the *EoL process efficiency and effectiveness* is a key variable.

*EoL process efficiency and effectiveness* is a variable that covers all operations at the battery EoL stage, from disassembly to recycling. It directly affects the potential of *Batteries gaining 2nd life, Recyclability of battery*, along with the *Recycling rate* itself. Being able to swiftly and effectively assess the condition of the

EoL battery, disassembling it without additional damage and determine its future reduces the operational cycle time of each battery, and enables it to bring value to multiple stakeholders sooner. It also directly impacts the recyclability of each battery, since having the necessary data and easily disassembled design lowers the risk of black mass contamination and waste products, as well as facilitating better data-driven decision making. Additionally, recycling processes would be more efficient since many of the safety precautions could be mitigated by having the necessary data available. It could also then directly lower remanufacturing costs of batteries applicable for second life through its circular design and potentially lower recycled material costs, since recyclers could offer better pricing for OEMs directly supporting their operations [Expert B].

As was discussed earlier in this thesis (RQ1), the findings point to EoL problems being the effects of two causes: the uncircular design of batteries and the lack of access to BoL data at the EoL stages. Therefore, to increase the efficiency and effectiveness of EoL processes, battery designs should be more circular and BoL data should be accessible at the EoL stage. But in order to be able to design circularly, the battery designers at the battery's BoL need access to EoL data. As was also found in this thesis (RQ2), there are several enablers of these data exchanges. Design guidelines and standards, performance reporting and design testing are all tools for BoL designers to gain insights into EoL processes. The same applies to design consulting, direct sharing and data platforms, but these additionally enable data exchange in the direction as well. The DPP will be a vital tool for EoL actors to gain access to BoL data.

In summary, the model demonstrates how adopting a circular business model like BaaS incentivizes the creation of a closed-loop system where materials, information, and financial value flow continuously. The circularity of the system has the potential to reduce costs, bring sustainable recurring revenue, and align with the rules and regulations of the future industry.



**Figure 4.4:** System Dynamics Model of How BaaS Incentivizes Data Transparency and Circular Product Design

# 5

## Discussions

This section provides both an exploration of the methodology used in the thesis and its limitations, which can be valuable for future work. Additionally, the findings related to the three research questions are presented.

### 5.1 Methodology Consideration and Limitations

#### 5.1.1 Literature review

##### Use of PRISMA for Structure Literature Review

The systematic literature thesis following the PRISMA framework is adopted as the initial process to understand the concept of the thesis. This approach also helps to identify gaps from the previous thesis. Furthermore, it is not only beneficial for ensuring transparency of the literature review process but also provides a rigorous framework that facilitates researchers when conducting the analysis throughout the thesis.

##### Reliance of Academic Sources

This thesis is mainly based on academic sources, which were believed to be more reliable. However, the EV industry and recycling technology are rapidly evolving over time, resulting from many uncontrollable factors, such as politics, economics, and technology. This significantly affects the EV market and causes uncertainty. Therefore, the thesis may overlook emerging trends that are yet to be explored academically.

##### Gaps in Literature on Emerging Topics

It's important to note that there are limitations in the literature, especially in relation to data exchange mechanisms. And the limited literature that is out there are usually attributed to the same authors. While these authors might have expertise

in the field, only receiving information from one group of individual could bias the outcomes of the research.

### **5.1.2 Stakeholder Representation**

Participant selection of the research plays a major role in data collection phase. Given the complexity of the EV ecosystem, which involves a wide range of stakeholders, selecting the relevant and representative participants is crucial. To address this, we used a stakeholder analysis framework to guide this process. However, several constraints, including time constraints and limited responses can pose challenges to the process.

#### **Stakeholder Analysis Assessment**

While the EV value chain involves diverse stakeholders with different perspectives, not all were represented in the interview process due to time and feasibility constraints. To ensure that the most relevant perspectives were included, a stakeholder analysis framework was used to guide the selection of interviewees and improve the relevance of the collected insights. Although this approach offers a solid foundation, it still does not address the differences between different EV battery value chains. This therefore risks that the results might not be generalized for all EV battery value chains.

#### **Exclusion of Policymakers and Use of Secondary Sources**

As previously stated, the interview does not include policymakers who demonstrate strong interest and power due to time and feasibility constraints. Hence, the battery regulation frameworks are exclusively utilized as the data source representing the views of this stakeholder group.

#### **Challenges in Interview Participation and Sample Size**

Based on the stakeholder analysis, we contacted several leading companies, particularly automotive OEMs and recycling firms. However, there were still only a limited number of interview participants that we were able to get in contact with. The small sample size may be insufficient to generalize the data collected from these stakeholders and might risk result bias.

### **Industry Segment Bias in Interview Responses**

Another important consideration is the structural difference among actors within the EV value chain. Different OEMs show varying levels of control across the value chain. While some leading car manufacturers pursue vertical integration and invest in their own recycling plants, others have focused on manufacturing and partnering with recycling actors. This variation can potentially lead to different insights and viewpoints and might affect the findings of our thesis, again possibly compromising generalizability.

#### **5.1.3 Confidentiality Due to Industry Competition**

The high degree of competitiveness and secrecy in the EV battery industry is one of the challenges that hinders our ability to collect data. Some insights are confidential creating difficulties to gain deep insights on certain topics, such as the business strategies and battery design concepts related to proprietary technology.

#### **5.1.4 Verification**

Not every individual in the value chain agrees on every single topic. That, in combination with the small sample size we were able to get in touch with, can lead to result biases. For future research, it would be interesting to see how our findings align with value chains found in other countries where opinions and viewpoints might differ.

#### **5.1.5 Modelling**

While the SD model provides a useful high-level visualization of the interactions between key variables of the system, some limitations should be acknowledged. First and foremost, although it was purely based on findings from the research, some basic assumptions had to be made. These are that increased sales lead to increased sales revenues, increased production requires an increase in materials, and each EV contains a battery. The scope for increased feasibility is also very narrow. OEM profits are, for example, determined by various factors in the real world, but the model only considers four of them. As well as the revenues and costs are determined in a simplistic and intuitive way since the model's sole purpose is to highlight incentives and provide a basis for further research.

Although SD offers the opportunity to quantify model variables and simulate, this was not performed in this thesis. This means that the relationships between

variables were not tested for their sensitivity, strength, or behavior over time. It was only built with the goal of visualizing the system and how the system variables affect each other on a high level. This step could be addressed in future work to increase the usefulness of the models for assessing numerical implications, such as profitability compared to the current linear model. This step was not performed in this thesis due to the project's time constraints since getting verifiable empirical data for all model variables is a time-intensive process, along with having some feasibility concerns.

The model also operates at a generalized level across the EV battery value chain. As discussed several times in the thesis, variability between different EV value chains is high. The model is therefore on a very high level. It does not distinguish between regional variations, different battery chemistries, or value chain specific structures, all of which could influence the dynamics of the different systems.

Overall, the SD model should be seen as a first step toward a more complete simulation model that can analyze strategic decision-making and policy development. In its current form, it serves as a conceptual foundation that highlights key variables and the relationships between them, but it requires further work for practical usefulness.

## 5.2 Implication of the Results

The findings from this thesis cover quite a lot of ground. Each research question builds upon the previous question. RQ1 aims to discover the processes and key challenges that are problematic. RQ2 revolves around exploring potential tools that could mitigate these problems. RQ3 showcases how a change in business model can create financial incentives to implement these tools and mechanisms to mitigate the problems. All together, these findings paint a holistic picture of the EV battery value chain and can be helpful when designing, managing, and governing new circular EV battery systems.

### 5.2.1 RQ1 : What limits the efficiency and effectiveness of current EV battery disassembly practices?

As presented in the findings of RQ1, the EoL processes, and problems related to product design and the lack of data were examined. Although this research focuses on the challenges in disassembling, providing the comprehensive key activities associated with EoL handling can better illustrate and identify the gaps in today's

operations. These five steps, which are collecting and transportation, testing and discharging, disassembly, shedding and mechanical separation, and refining, are simplified processes from data collected from literature, interviews, and site visits.

The real operation is complex and can contain several different subtasks. The difference in sub-procedures could be due to variations in battery design and several factors such as resources, technology advancement, and regulations. This can be observed from interviews with recycling firms that have different resources and competencies. While one manually operates the disassembling, another claimed that its operation is more efficient because of advanced disassembly technology. Thus, the differences in approach highlight that even the standardization of the EoL process is necessary to streamline the process and increase efficiency, a one-size-fits-all model may not be applicable due to the diversity in design, operational capacity, and market maturity.

Product design is one of the most prominent challenges in the battery disassembly process. The design-related challenges identified in the literature are consistent with the insights gathered from the interviews and site visits. However, while the use of non-detachable joints and adhesive is frequently discussed in the literature as one of the major challenges, the real-world implications extend beyond dismantling difficulty. The recovered black material may get contaminated by adhesives and residual particles, which will dramatically decrease its purity and market value and cause more issues for recyclers.

Interestingly, today's battery designs are mainly optimized for durability, performance, and safety rather than circularity. This emphasized the conflicts between performance-driven design requirements and recyclability. As revealed by industry experts, this tendency is highly unlikely to change soon. More importantly, the increasing competition in the EV market may further reinforce these design priorities.

To tackle this disassembly issue, improving data accessibility to battery-related data has been proposed as an enabler to drive the recyclability of the EV battery. However, IP protection and competitive pressures remain key obstacles to transparent data sharing among OEMs, recyclers, and other stakeholders. As well as, even if the data is available and shared across stakeholders, the data quality still requires trust and reliability.

The EoL management considerations for EV batteries extend beyond optimizing the processes for cost and efficiency. Safety is the most critical concern, as batteries contain hazardous chemicals that can easily trigger fires and explosions, which pose significant risks. Varying battery conditions during the use phase further complicate safe handling. Thus, gaining access to battery-related data is essential,

and that data must be accurate to ensure reliability when it comes to safety.

### **5.2.2 RQ2: What tools and mechanisms could enhance data transparency for better EV battery EoL process performance?**

This research question explored and examined different tools and mechanisms that could assist in mitigating the problems identified in RQ1. The different tools were categorized into three different information flow categories: through material flow, through 3rd party actors, and through direct collaboration. For the material flow, there was only the DPP. The DPP will play a key role in enabling value chain transparency. It has strong regulatory backing and high requirements on the data that should be embedded. Other tools and mechanisms, such as data platforms, design consulting, and performance reporting, were also identified. However, these tools and mechanisms are less structured and well-defined than the DPP.

Given its important role in the future, a sufficient amount of literature regarding the DPP could be found. However, this cannot be said for the other mechanisms. Many other mechanisms identified in this thesis were discovered through interviews and industry and do not have explicit academic literature available, at least not in the context of EV batteries. These mechanisms were adopted by industry, with different actors and value chains adopting different mechanisms, to combat the lack of data transparency while seemingly having no standard frameworks to adopt. That means that the nature of these mechanisms might vary depending on who is being interviewed and which value chain that interviewee is a part of. Thus, the findings of this research question might not be totally generalizable, especially regarding other value chains in other parts of the world. This goes for what mechanisms are available and also how they are practiced. This apparent misalignment between academia and industry might pose an opportunity to further research these mechanisms and offer rigid frameworks for the industry to adapt for maximum structure and usability. Although it should be acknowledged that some literature might exist on this topic, some may not be included in the research. However, this still means that the accessibility and quantity of literature are suboptimal.

The findings of this research question can be considered useful in a few different ways. For industry, the identification and analysis of these mechanisms might inspire value chains and their actors that do not have these tools and mechanisms implemented to implement them. Especially if the problems listed in RQ1 are relevant to their position. The findings showcase the identified positives and drawbacks

associated with each tool and mechanism, giving these actors a strong base to make an implementation plan suitable for their situation. For academia, these findings are useful as the basis for further research. It highlights the potential of creating structured frameworks to bridge the apparent gap between academia and industry in this context.

### **5.2.3 RQ3 How can Battery-as-a-service support and incentivize data exchange within the EV battery value chain?**

BaaS is the business model that builds on the concept of servitization and CEBM. It is one of the business use cases that tackles the challenges of EV circularity-related data sharing issues by shifting the ownership of the battery from car owners to car manufacturers, which contrasts with traditional approaches.

By using the CBMC to present the BaaS model, we can identify eleven key elements, including value proposition, customer segmentation, customer relationships, channels, key partners, key resources, key activities, cost structure, revenue stream, take-back system, and adoption factors. Most of the findings are interpreted from the data collected in the academic papers, which align with the insights from industry experts. However, the real-world implementation of BaaS is considerably more complex than that analyzed in this thesis.

It is important to note that each key component of the business model canvas, especially the take-back system and adoption factors, requires more in-depth analysis. The reverse logistics necessary to support the takeback system are complicated for reasons such as non-standardized products, the inherent value of the material, the decision to centralize or decentralize drop-off points, etc. Efficient logistics operations demand both competency and collaboration. Furthermore, several external factors can influence the adoption of this business model. While some scholars debate customer perceptions regarding ownership of batteries, there may be early adopters who can be targeted effectively.

The SD model, although subject to strict limitations, illustrates how BaaS can incentivize data transparency and circularity in the EV battery value chain. As discussed in detail above, more work is required for the practical use of the model in the industry. In its current state, it serves as a strong basis for further research to build on top of it and quantify it for simulation. With more development, it could prove a useful tool in strategy development.

### 5.2.4 Implications of the Thesis as a Whole

All in all, the thesis aims to identify the problems seen at the EoL stage in the EV battery industry today, and investigate what mechanisms can help mitigate them and how to enable their adoption through a change in business models. One prominent theme can be extracted from this thesis, and that is that collaborations and cooperation will be key to unlocking circularity. With the Battery Regulation enforcing stricter policies every year, automotive OEMs are in a strong position to align their value chains and operations with the industry of the future. There are many examples of incumbent firms that fail to adapt to changing industry environments and end up withering away as a result. The results gathered in this thesis and further research on similar topics provide strong evidence-based starting points for industry actors to drive systematic change in their value chains.

Data transparency is crucial for enhancing end-of-life performance, which ultimately results in greater circularity. This is because data transparency serves as the basis for circular designs (designers have access to EoL data) and enables more efficient and effective EoL processes and decision-making. To incentivize an increase in data transparency and collaboration, the industry has to pay attention to new directions regarding business models since the current business practices offer no incentives for such topics besides goodwill. BaaS is one potential business model for OEMs to implement. This thesis showcases, on a high level, how this business model could increase OEM profitability, therefore enabling circular thinking and design. Aligning business model innovation with circularity should, therefore, be prioritized for OEMs in their journey of shaping the industry of the future.

# 6

## Conclusion

This thesis explored the challenges and barriers of circularity in the current EV battery industry. Next, it explored how these problems could be addressed through improved data transparency and how that could be incentivized by circular business models. The findings showcase that the problems of the industry are systematic, with information silos and lack of economic incentives playing key roles.

This thesis offers several key insights regarding EV battery disassembly challenges, data exchange mechanisms and the potential of BaaS as a circularity enabler. EoL problems are caused by both product design-related problems and data-related problems. The key to address the product design-related problems is increased data transparency and incentives. Battery designers need access to EoL data to effectively meet their requirements, and there must be an incentive structure in place to enable the circular design.

Data transparency was investigated by identifying and analyzing data exchange tools and mechanisms. Several mechanisms were identified, such as the DPP and data platforms. These mechanisms, although each of them have some implementation barriers, show promise to increase transparency in the value chain.

The incentive structure was investigated by illustrating how circular business models (BaaS in this thesis) can incentivise increased data transparency and therefore increasing circular thinking in design and operations. By retaining ownership, OEMs have an incentive of limiting EoL waste and extracting as much value out of their asset as possible, therefore incentivizing efficient EoL operations for giving batteries a second life or efficient recycling.

The main theme overarching this thesis is the need for stakeholder collaboration in the value chain. These problems can not be solved by local optimization but rather system wide optimization. Ultimately, this thesis provides a foundation for both future research and practical implementation to contribute to the ongoing transformation towards a circular EV battery industry.



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# A

## Appendix 1 - Interview Questions

The questionnaires below are grouped by topic. Questions are tailored to each expert group to ensure relevant and meaningful insights.

### **Expert Background**

- Could you please introduce yourself?
- Can you provide some background about your work/project and responsibilities?

### **EoL Process and Challenges**

- Could you walk me through the typical steps involved in the EV battery recycling process at your facility, from arrival to final material output?
- How is the current business model for a recycler? Where does your income come from?
- What are the most common challenges/bottlenecks you face when disassembling EV batteries for recycling?
- What kind of data do you currently collect and use in your recycling process?
- What data would be most valuable to improve the efficiency of the process?

### **Design Parameters Trade-off**

- What are the main trade-offs between recyclability and other design priorities (e.g., cost, performance)?
- Do you think battery manufacturers consider recyclability in their designs? What improvements would you suggest?

### **Circular Economy of EV Battery and Collaboration**

- What are the current barriers to creating a truly circular economy in general?
- What factors make transparency in EVB supply chains difficult?
- What are the biggest barriers to effective collaboration between designers and recyclers you have found in your experience?
- What is your current level of communication with EoL recyclers/disassemblers or other stakeholders?

### **Mechanisms for Increasing Circularity**

- How does your product work? Can you walk us through?

- Do you think data transparency is enough to drive CE?
- What factors make transparency in EVB supply chains difficult?
- What are some practical ways/mechanisms to bring battery designers and recyclers into the same conversation during the design phase? Current ways of working
- Digital product passport for increased traceability
  - What do you think about DPP?
  - What are the main barriers to DPP integration?
  - Do you think DPP can be a key enabler for the circular economy for EVB batteries?
  - How does it work?
- How can digital solutions, such as Battery Passports or traceability systems, help improve transparency and sustainability?
- From your perspective, what are the most promising innovations driving circularity in the EVB sector?
- Have you seen any industries or product categories that successfully align design and recycling?

### **Incentives & DfC**

- How can the ease of disassembly be measured for a reward structure of circular designs?
- What incentives can drive stakeholders, particularly battery designers, to share detailed design information (including disassembly considerations)?
- Have you come across any business models that have been implemented?

### **Future Trend**

- Have you seen any industries or product categories that successfully align design and recycling?
- What advice would you give to battery designers and manufacturers to improve the recyclability of their products?
- How do you see EV battery recycling evolving in the next 5 years?

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