Electrical vehicles batteries lifecycle: Return center capabilities

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May 2024

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Acknowledgments

First, I would like to thank the Volvo Group and most specifically Volvo Energy for inviting me to join their discussions and to challenge myself in developing this master's thesis. I felt warmly welcomed from day one and enjoyed the time there even if it was only for a short period of time. Mostly, my thanks go to Fredrik Engblom. Your sharp thoughts and interest in a sustainable innovation are inspiring and I am grateful to have worked with you. I would also like to thank the BRC workshop group lead by Jerome Perez and all interviewees who accepted my requests to participate and offered valuable input to this thesis.

I would like to express my gratitude to Sandeep Jagtap. Your guidance as my academic supervisor has been precious throughout this period. Your advice and expertise have greatly enhanced the scope and coherence of this thesis. I am greatly thankful for your constructive feedback, your flexibility and availability.

Furthermore, I want to extend my profound thanks to my family for their endless and unconditional support throughout my life and academic journey. You have always backed my decisions, and I am deeply grateful for the love we nurture. A special thanks to the incredible person that is my wife. I feel like the luckiest person in the world to have you by my side. Thank you for standing by me through all the harsh times and for supporting even my craziest ideas. I can only hope to repay you with the same amount of love.

I wish to say a big thank you to Lund University and all the staff from LTH, for creating the place where my life changed completely to a new and brighter future. Lastly, a special thanks also to the Lund Global Scholarship, without you I wouldn't even be here.

Abstract

The combined rise on the demand for electrical vehicles for road transportation, technological advancements for Lithium-Ion batteries, and limited availability of rare metals, create a need for sustainable solutions for Electric Vehicle Batteries (EVBs) at the end of their first life. This makes companies rethink on how to deal with the increased complexity generated by the exponential growth of EVBs that will soon be on the return flow for second life preparation. Moreover, limited research is found for the specific processes in this reverse logistics.

Therefore, the purpose of this thesis was to explore the capabilities required in the electric vehicle industry for creating an effective connection between the returning after-first life EVBs and prior to their second life applications, in response to the evolving customer demands and industry trends. For that, this research uses a combined multiple and single case study approach to explore how a vehicle manufacturer could innovate its business model to implement an efficient, flexible, and scalable Battery Return Center.

The main capabilities for a Battery Return Center were identified by reviewing existing literature and regulations in place for the European Union. Current return flow strategies, their operationalization, and primary challenges and success factors are identified by conducting interviews with representatives from six different reference companies in the industry. Finally, a potential Battery Return Center framework design and implementation at Volvo Group are explored through a twelve-week workshop with four employees that are involved in the EVBs' lifecycle.

The results express that the capabilities may be shaped in different ways, but there is a clear path connecting them to create a return flow. It was discovered that the companies involved in the second life solutions for EVBs have different strategies and offer different products or services, but all share the same drive for innovation and sustainability. While the operationalization of the capabilities is similar, each company have many specific processes connected to internal factors, advocating for the fact that there is no single optimum solution for designing a return flow of EVBs. All capabilities were found to require close collaboration among the whole supply chain to increase standardization and to create a cost-efficient solution. Furthermore, the necessity to make a design that prioritizes flexibility and that embraces the scalability for different solutions and strategies was emphasized.

Keywords: *Electric vehicle batteries; Reverse logistics flow; Circular economy; Battery return center; Electric vehicle batteries' lifecycle*

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Abbreviations

EV	Electric Vehicle
EVB	Electric Vehicle Battery
LIB	Lithium-Ion Battery
CE	Circular Economy
EU	European Union
PHEV	Plug-in Hybrids Electric Vehicle
HDEV	Heavy-Duty Electric Vehicle
LDEV	Light-Duty Electric Vehicle
EOL	End-of-Life
SOH	State of Health
SOC	State of Charge

1. Introduction

The introduction chapter aims to present the background of the thesis, define the problem at hand and explain the purpose of this study. Further, the research questions to be answered will be introduced. Lastly, the audience to whom this thesis may be important is addressed and the complete structure of the following chapters will be presented.

1.1 Background

Road freight transportation has been on a slow, but steady, growth since the year of 2012 and continues to be the main mode of transportation in the European Union, representing 77.3% of total inland freight transport in 2021 (Statista Research Department, 2023). The role that cargo vehicles have, not only in the EU but in the world's economy, is solidified by now, hereafter new technologies are constantly being explored to increase their efficiency and, particularly, the environmental impact (Muratori et al., 2021; Zhang et al., 2023).

The electrification of road transportation, involving the transition from traditional internal combustion engine vehicles to electric vehicles (EVs), is gaining momentum as a crucial step towards sustainable urban development (Dia, 2019). Despite the slow diffusion of EVs, policymakers widely recognize electrification as a key measure for decarbonizing road transport and reducing the environmental impact associated with oil dependency (Knobloch et al., 2020). Studies have shown that electrification can lead to significant reductions in greenhouse gas emissions, contributing to global climate change mitigation efforts and potentially achieving zero emissions by 2050 (Zhang & Fujimori, 2020; Khalili et al., 2019). Moreover, the electrification of road transport increasingly extends beyond light-duty vehicles to include heavy-duty vehicles, buses, and off-road equipment (Hao et al., 2019).

The adoption of EVs and the electrification of road transport are not only beneficial for the environment but also have broader economic implications. Research indicates that the electrification of road transport can have economy-wide impacts, with models showing the potential for significant changes in the energy mix and reductions in public health overload from outdoor air pollution (Kazemzadeh et al., 2022). Furthermore, electrification can lead to the development of new infrastructure, such as electric chargers on roads, which can help accelerate the adoption of electric vehicles and contribute to the decarbonization of the transportation sector in general (Coban et al., 2022). Simultaneously, many governments, especially in the European Union, are creating development plans to support the adoption of EVs, as well as plug-in hybrids electric vehicles (PHEVs), for both urban and road transportation of goods and services as a preferred alternative to reduce the CO2 impact in the atmosphere, air pollution and noise in the cities (European Commission, 2019; Tankou et al., 2023).

Although electric vehicle batteries (EVBs) are at the forefront of discussions concerning innovation and the future of road transportation, the convergence of EVBs with Circular Economy (CE) is the key for the nurturing of a sustainable business (Tripathy et al., 2022). Together, EVBs and CE principles will have a symbiotic relationship aimed at sustainability and resource efficiency and a pivotal aspect of this association involves prolonging the utility of EVBs beyond their initial automotive application (Tripathy et al., 2022). In fact, EVBs do not necessarily need to be disposed of straight away as they can potentially be refurbished, remanufactured, repurposed, or recycled (Olsson et al., 2018). Moreover, integrating EVBs into second-life solutions bolsters material circularity within the CE framework. Instead of adhering to a linear "take-make-dispose" model, which culminates in waste generation, a closed-loop system is advocated to delay the demand for new battery production and raw material extraction, enabling, for instance, the reduction of environmental impacts associated with manufacturing (Geissdoerfer et al., 2020; Kazemzadeh et al., 2022).

1.2 Problem definition

In the process of moving towards an electrified vehicle fleet, the demand for these vehicles is currently on the rise and the expectation for the future is that this tendency will grow quite sharply in the upcoming years (Zhang et al., 2023). Consequently, according to the International Council on Clean Transportation (ICCT), the scaling up on the sales for light and heavy-duty electric vehicles (HDEVs) and PHEVs will generate a global amount of around 1.2 million batteries in their End of Life (EOL) in 2030, rising to 14 million in 2040 and reaching the level of 50 million by 2050 (Tankou et al., 2023).

Logically, as the number of sales and EVs on the road grows, so will the volume of batteries reaching their EOL stage. Therefore, accurately predicting the timeline and scale of EVBs retirement is crucial, as this information can guide investments from both public and private sectors (Tankou et al., 2023). Strategic decisions can be made regarding research and development, processing facilities for reuse and recycling, and securing a sufficient supply of raw materials. However, one of the enablers of this transition will be the reverse logistics flow of EVBs at the end of their first life. This involves the transportation of goods to their final destination, with the purpose of extracting value through EOL management practices, while also promoting sustainability (Prevolnik & Ziemba, 2019). The expressive numbers of batteries in their EOL for the next decades urge for the development of smart EVBs second life solutions that consider both the CE aspect but also a profitable business model that companies fell interested to invest on. In that sense, the return logistical flow of EVBs at the end of their first life is a crucial step in the foundation of the EVB lifecycle and the critical link between EVBs' first and second life (Yang et al., 2022).

Previous academic literature has been focusing on investigating the different applications and solutions for the recycling of LIBs, such as the life cycle assessment (Zhang et al., 2023; Chen et al., 2019; Chen et al., 2022; Beaudet et al., 2020; Pražanová et al., 2022), technical aspects for the material recovery efficiency and technological processes (Tao et al., 2021; Castillo-Martínez et al., 2022; Li et al., 2023b; Miao et al., 2022; Larouche et al., 2020; Yun et al. 2018), and comparing different recycling methods recovery efficiency or environmental impacts (Bhar et al., 2023; Gaines & Wang, 2021; Yun et al., 2018; Larouche et al., 2020; Makuza et al., 2021, Dunn et al., 2021; Idjis & da Costa, 2017). Different second life applications have been investigated, specially focusing on the repurposing possibilities, trying to evaluate real life cases and to explore feasible solutions for larger scales (Song et al., 2022; Catton et al., 2019; Thakur et al., 2022; Russell & Nasr, 2023; Canals Casals et al., 2017; Debnath et al., 2016; Assunção et al., 2016; Wu et al., 2020). Additionally, studies also explored strategies for the repurposing processes of LIBs (Lee & Kum, 2019; Zhang et al., 2021; Jiang et al., 2021; Lai et al., 2019), and it is also possible to identify an overview of the environmental benefits and risks of second life EVBs solutions (Sathre et al., 2015; Wilson et al., 2021; Richa et al., 2017; Tao et al., 2021; Cusenza et al., 2019).

However, limited research is found on the specific processes for the reverse logistics of EVBs after the end of their first life and prior to the beginning of their second life applications, from a supply chain perspective. Specifically, the roles, relations, activities and regulations in this reverse flow. There are some examples of exploration in this area, such as the work of Prevolnik & Ziemba (2019) for the investigation of how reverse logistics networks of LIBs are currently set up, and to create an overview of how the different actors and processes are connected. Also, the work done by Li et al. (2023b) that performed a comprehensive review of second life batteries and described some of the reverse logistics steps involved in the repurposing of LIBs. Nevertheless, no prior research has focused on the internal organizational capabilities needed for companies to implement this reverse logistics. This, however, is important as an integral part of the CE process, especially taking into consideration the scalability needs, complexity and challenges that EVBs will impose in the near future. Thus, further research is needed to understand internal factors and the role and opportunities of a Battery Return Center (BRC) in the return logistical flow of EVBs after the end of their first life application.

1.3 Research purpose

The purpose of this thesis is to explore the capabilities required in the EV industry for creating an effective connection between the returning after-first life batteries and prior to their second life applications, in response to the evolving customer demands and industry trends.

To identify these capabilities, it is needed to initially understand the current academic background and technological applications. Therefore, this thesis will investigate the complete scenario around the return flow of EVBs and provide a detailed description of their reverse logistic processes. Additionally, it will examine how this flow is currently executed by many reference companies in the industry, what are their best practices, challenges, and perspective of future. Ultimately, this information will help determine the critical capabilities required for a successful return flow of batteries and how they are connected to each other.

1.4 Research questions

In order to address the described problem, the aim of this study is to explore what would be an optimal framework for the return logistics flow for EVBs at the end of their first life, including the capabilities for a BRC where the preparations and decisions for a second-life applications are done, with Volvo Group as a case study. To contribute to this aim, the following research questions (RQs) are:

RQ1: What model capabilities are necessary for a BRC from a supply chain perspective?

RQ2: What are the best practices for the Reverse Logistics of EVBs at the end of their first life? How and why are companies performing in this way?

RQ3: How should Volvo Group design its BRC reverse logistics in the EU?

1.5 Audience

This thesis targets two main audiences, the first being industry professionals, which includes practitioners at the case company, Volvo Group, who are interested in exploring the possibilities for a return flow of EVBs and the capabilities for a BRC. Similarly, other automotive companies can benefit from the findings related to a BRC implementation and the insights are also valuable for organizations across the EVBs value chain considering batteries' second life solutions.

Secondly, this thesis contributes to the growing body of research on the area of EVBs' second life. It focuses on the current state of batteries' reverse flow implemented in the automotive industry and explores the non-technical aspects of closed-loop supply chains. On a broader scale, the results offer policymakers a deeper understanding of the relationship between regulations, barriers to the implementation and development of solutions for second life EVBs. This knowledge can be used to develop and implement policies that encourage environmentally sustainable life cycles for EVBs within the automotive sector.

1.6 Disposition

Chapter one introduced the background to this research, defined the problem, the purpose of the thesis, the research questions, as well as the targeted audience.

Chapter two presents and justifies the methodology, research design, and case study approach in this thesis. Then, the process of data collection and analysis as well as the research quality, scope and limitations, and ethical considerations are discussed.

Chapter three provides a literature review of the most relevant theoretical concepts for this study and the current state of research regarding EVBs, CE strategies and BRC capabilities. The chapter closes with a summary of challenges for a BRC implementation.

Chapter four introduces and delves into the conceptual framework developed for the empirics and analysis of findings.

Chapter five discusses and contextualizes the findings by relating them to the existing literature and highlighting this research's contribution to the state of knowledge. Furthermore, methodological reflections are provided.

Chapter six concludes this thesis with a summary of the findings and recommendations for practitioners, policymakers, and for future research.

2. Methodology

This chapter explains the methodology of this thesis used to produce knowledge and answer the previously established research questions. It introduces the research design and case study approach in section 2.1, methods for data collection and analysis in sections 2.2 and 2.3, exposes the explanation of the research quality in 2.4, discusses the scope and limitations in section 2.5, and ends with ethical considerations in section 2.6.

2.1 Research design

This thesis draws on a transdisciplinary approach, reflecting the researcher's interdisciplinary background. Researching and understanding the relation between CE and the processes for the reverse logistics of EVBs in the end of their first life requires an interdisciplinary lens as they fundamentally encompass various disciplines, such as business, environment, and politics. Furthermore, this research embodies the principles of transdisciplinary research, as characterized by Lang et al., (2012):

Collaborative problem framing: All relevant stakeholders contribute to defining the research question and its scope.

Co-production of knowledge: Researchers and stakeholders work together to create "*solution-oriented and transferable knowledge*" through collaborative research.

Integration of knowledge into practice: The research findings are directly applicable to both scientific and societal contexts.

This approach has been proven valuable in addressing real-world sustainability challenges, as it fosters knowledge directly applicable to solving the problem at hand (Wickson et al., 2006; Lawrence et al., 2022).

2.1.1 Conceptual design

The conceptual research design, as shown in Figure 2.1, followed the principles present in two well-known business model innovation (BMI) processes, being the first proposed by Geissdoerfer et al. (2017) and the later by Wirtz & David (2018). To achieve a better fitting to the problematic explored in this research, the author combined the main initial steps of both the traditional BMI processes. Initially, the analysis of the current situation is explored through several academic sources, which, in this case, means the adoption of CE strategies and the operational requirements and regulations for dealing with second life EVBs. After that, follows the identification of the operational flow and influencing factors, both at Volvo Group and other companies in the world that are having success in implementing a return flow of EVBs after the end of their first life. Lastly, the concept design of a new BRC for Volvo Group's individual scenario is discussed and idealized.

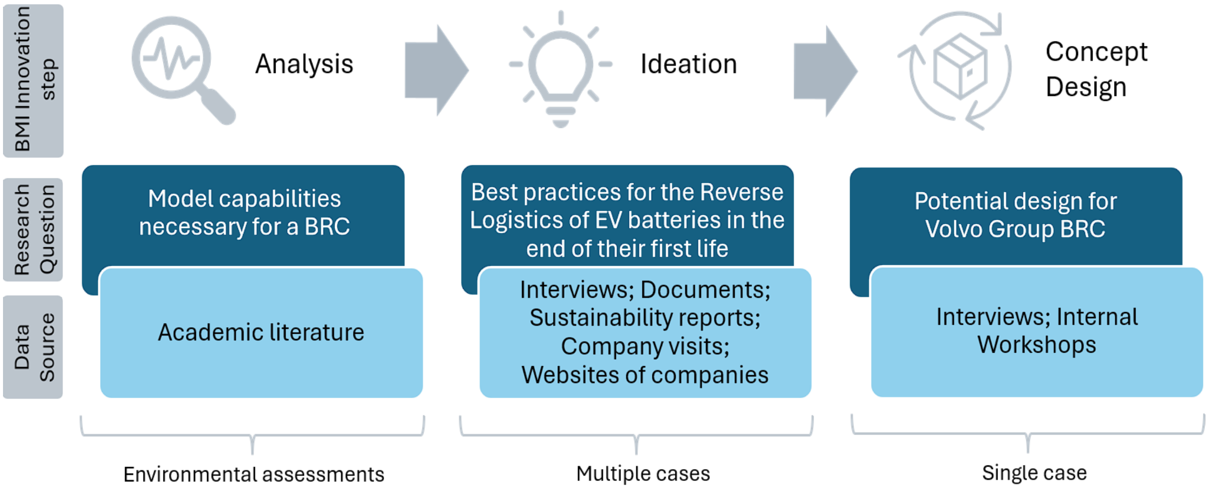

Figure 2.1 - Conceptual research design.

Source: Author

2.1.2 Case study

The case study approach is a valuable research method utilized across various disciplines. This method allows researchers to explore, describe, and analyze situations in detail, providing rich insights into the subject under study (Levy, 2008). It involves an in-depth investigation of a single instance (single case) or a small number of instances (multiple case) within their real-life context to understand complex phenomena (Gagnon, 2009). While single case research typically delves into a significant phenomenon under unique circumstances, allowing for an in-depth exploration of a specific case, the multiple-case approach enables researchers to study many instances of a phenomenon, providing a broader perspective and enhancing the robustness of the research (Eisenhardt & Graebner, 2007). This thesis employs a multi-method approach to gain a comprehensive understanding of the research questions. To answer *RQ2*, multiple cases from the EVB industry are analyzed. This enables the identification of recurring patterns and themes related to the adoption of CE strategies and supply chain designs for the reverse logistics of EVBs to provide a basis for potential generalizability across the industry. Volvo Group then serves as a single case study to delve deeper into the business model concept design process, applying world's best practices and regulations to their unique context. Thus, this research effectively combines broad-level understanding obtained from several less in-depth cases with the focused, contextualized analysis provided by a single, detailed case study.

The adoption of a combined multiple and single case study approach in this thesis is driven by two primary factors. Firstly, single case study methods have been extensively utilized in academic literature to exemplify how companies innovate their business models by creating solutions and applications for the second life of EVBs (Jiao & Evans, 2016; Vu et al., 2020; Colarullo & Thakur, 2022). Given the high dependency of closed-loop supply chains and CE (Chizaryfard et al., 2023) and the contextual nature of the reverse logistics for the second life of EVBs, employing a single case study allows for a real-life setting and context-specific insights (Simons, 2015).

Secondly, there remains a lack of understanding regarding CE practical solutions for the second life of EVBs, as elaborated in Chapter 3. Scholars argue that this absence of case studies hinders companies from grasping the knowledge from peers and creating an understanding on how to perform a sustainable business innovation (Evans et al., 2017). Due to this knowledge gap, employing a qualitative and exploratory multiple case study approach is deemed appropriate. This methodology aids in testing existing theories with multiple cases in *RQ2*, while also facilitating the generation of new concepts and theories through the illustrative power of a single case study in *RQ3*.

2.2 Data collection

Multiple sources of data were triangulated in this research to construct internal validity: academic and gray literature, company documents, interviews, and workshops.

2.2.1 Literature review

This research utilized a comprehensive literature review incorporating both academic and gray literature. Academic sources included peer-reviewed journal articles, conference proceedings, and books, accessible up to February 2024. The initial search relied on relevant keywords, which were employed in various forms, including singular, plural, and combinations. Examples included: "heavy-duty electric vehicle" AND ("EVBs" OR “LIBs”) AND ("circular economy" OR "remanufacturing" OR "repurposing" OR "second life"). To ensure relevance, the titles, abstracts, keywords, and, if necessary, full papers were scrutinized. This went beyond simply searching for keywords, instead focusing on synonyms, comparable concepts, and thematic alignment with the research topic.

Given the rapid evolution of EVBs and related technologies, the literature review prioritized research published after 2014. More recent publications, specifically those after 2020, were given preference to ensure the research reflected current discourse and technological advancements. However, this timeframe restriction was not applied to foundational concepts such as circular economy definitions, circular economy strategies, business model innovation, and closed-loop supply chains.

Finally, a snowballing technique was employed to identify additional relevant literature. This technique involves reviewing the reference lists of selected papers to find further pertinent sources (Jalali & Wohlin, 2012).

The academic literature review served two primary purposes: First to define key concepts and summarize existing research on the research topic and second to gather relevant information specifically for answering *RQ1*.

The reviewed literature provided insights into:

1. Current understanding of CE: This established the theoretical background for the research.
2. Key features of the HDEVs business: This enabled the understanding of the drivers behind this industry.

3. An exploration of BRCs' capabilities: This provided valuable context for understanding the role of reverse logistics in the transition from first to second life of EVBs.
4. Previous research and regulations on the EVBs second life business: This offered a foundation for understanding existing practices and challenges in the specific context of EVBs, including relevant influencing factors.

Academic literature offered few details regarding the regulatory landscape governing EVBs and the tailored strategies adopted by companies to build up their capabilities in the reverse logistics flow to address a portion of *RQ2*. Consequently, supplementary insights were sought from gray literature sources. This included reviewing legal documents, companies' online platforms, sustainability reports, and consultant reports, like McKinsey. While the focus of the analysis was on the reverse logistics activities of a BRC within the EU, some of the advanced practices in the production were explored in countries of non-EU based companies, on the expectations to build up a knowledge that could be considered as carrying best practices in the world, but still respecting the regulations in place for the EU. Hence, the reviewed gray literature provided information on:

1) EU's current legislative regulations for EVBs and its potential future changes,

2) EVB life cycle strategies and their transition from first to second life in the automotive industry.

Therefore, the literature review not only provided a comprehensive overview of existing research and theories as background information but also furnished the necessary data for responding to the research questions.

2.2.2 Documents

To gain a comprehensive understanding of the case study, Volvo Group's documents and presentations were investigated. This analysis not only provided context but also yielded valuable data on their existing EVBs technologies, specifications, process flow and expectations for the future developments.

2.2.3 Semi-structured, unstructured, and informal interviews

The third set of data was gathered through semi-structured and informal interviews to address *RQ2* and *RQ3*. While the data extracted from gray literature for *RQ2* lacked depth regarding the motivations (why) behind companies performing reverse logistics for EVBs at the end of their first life and the specifics of implementing the processes and activities (how) required for that, a purposeful sample following a theory-based strategy (Palinkas et al., 2015) of companies providing 'second life EVB solutions', such as recycling, recovery and repurposing, was selected to delve into these aspects of the questions. Six semi-structured interviews were conducted with representatives from companies offering different solutions for second life EVBs. This interview format was chosen for its balance between providing a framework for discussion and allowing flexibility to explore participants' perspectives, objectively trying to improve the trustworthiness of the study, and making the results more plausible (Kallio et al., 2016). Appendix A contains a comprehensive list detailing the interviews, including the respondents' positions, as well as the date and time of each interview, however, as some of the respondents and companies chose to remain unnamed, it was decided to keep all participants under anonymous representations.

The author identified suitable interviewees either through companies' websites, social media or indicated by the company themselves after a direct contact. Interviews were conducted in either English or Portuguese, either in person or online. The interview guide was developed based on the literature review and initial findings from the gray literature on *RQ2*, with slight adjustments made during the research process based on insights gained from previous interviews. An example of the consolidated interview guide is available in Appendix B. As expected on an inductive research approach, the interview guide was not rigidly adhered to, allowing for the emergence of new topics or themes. With participants' consent, the interviews were electronically recorded to aid in adjusting interview notes. It was agreed with all interviewees that notes, recordings and final draft of this thesis could be shared upon request.

Internally to Volvo Energy, unstructured and informal interviews were conducted, both non-directive and focused (Adhabi & Anozie, 2017), in order to cover the initial knowledge, background and aspirations that the company envision for a Battery Return Center. Three employees were chosen for these in-depth interviews to explore Volvo's current second-life EV business model, internal factors influencing the creation of a BRC, and to develop BRC ideas. Interviewees were selected collaboratively with the company supervisor (Fredrik Engblom) and the information created was captured through detailed note taking. Lastly, the author participated in meetings related to EV life cycle management and had numerous informal conversations with Volvo employees, fostering a richer understanding of their work.

2.2.4 Workshop

To gain in-depth understanding of the single case company and its real-world operations, the author spent twelve weeks of the research period embedded within Volvo Energy's Battery Planning and Logistics team, located at CampX in Gothenburg. This consisted of a weekly participation in a workshop for the discussions of the design, capabilities, and challenges related to a model BRC for Volvo Group and an additional bi-weekly meeting with a Logistics Project Manager to present the thesis investigation findings and discuss their possible real-life implementation. The workshop was conducted together with one Logistics Project Manager, one Project Manager and one Core Technical Manager. This immersion facilitated close collaboration, providing insights into Volvo's current business model, its organizational capabilities, and access to data and interview candidates.

2.3 Data analysis

Thematic analysis is a well-established method for analyzing qualitative data that involves the identifying of patterns or themes within qualitative data, allowing for a systematic and structured examination (Braun & Clarke, 2006). Although initially introduced by Braun and Clarke in 2006, thematic analysis gained prominence as a structured and legitimate approach to data analysis in modern literature (Forbes, 2022). In thematic analysis, researchers aim to identify common themes based on content rather than form, focusing on deriving meaning rather than simply counting frequencies of words or utterances, but more than that, this method is particularly useful in uncovering patterns and trends within qualitative data, providing a structured approach to analyzing and interpreting information (Cernasev & Axon, 2023). There are usually five or six steps described for conducting a thematic analysis (Braun & Clarke, 2006; Cernasev & Axon, 2023), named:

Familiarization: Researchers become deeply immersed in the data by repeatedly reading and re-reading it.

Identifying Codes: Key phrases, words, or sentences that capture important aspects of the data are coded.

Theming: Codes are grouped into broader themes that represent significant patterns and concepts.

Reviewing and Defining Themes: Themes are refined, ensuring they accurately reflect the data and answer your research questions.

Write-up: Findings are presented in a clear and concise manner, showcasing the identified themes and their significance.

Furthermore, Naeem et al. (2023) proposed a systematic thematic analysis process for creating a conceptual model from qualitative research findings to help building up more structured and concise themes for the later exploration and analysis phase, as seen in Figure 2.2.

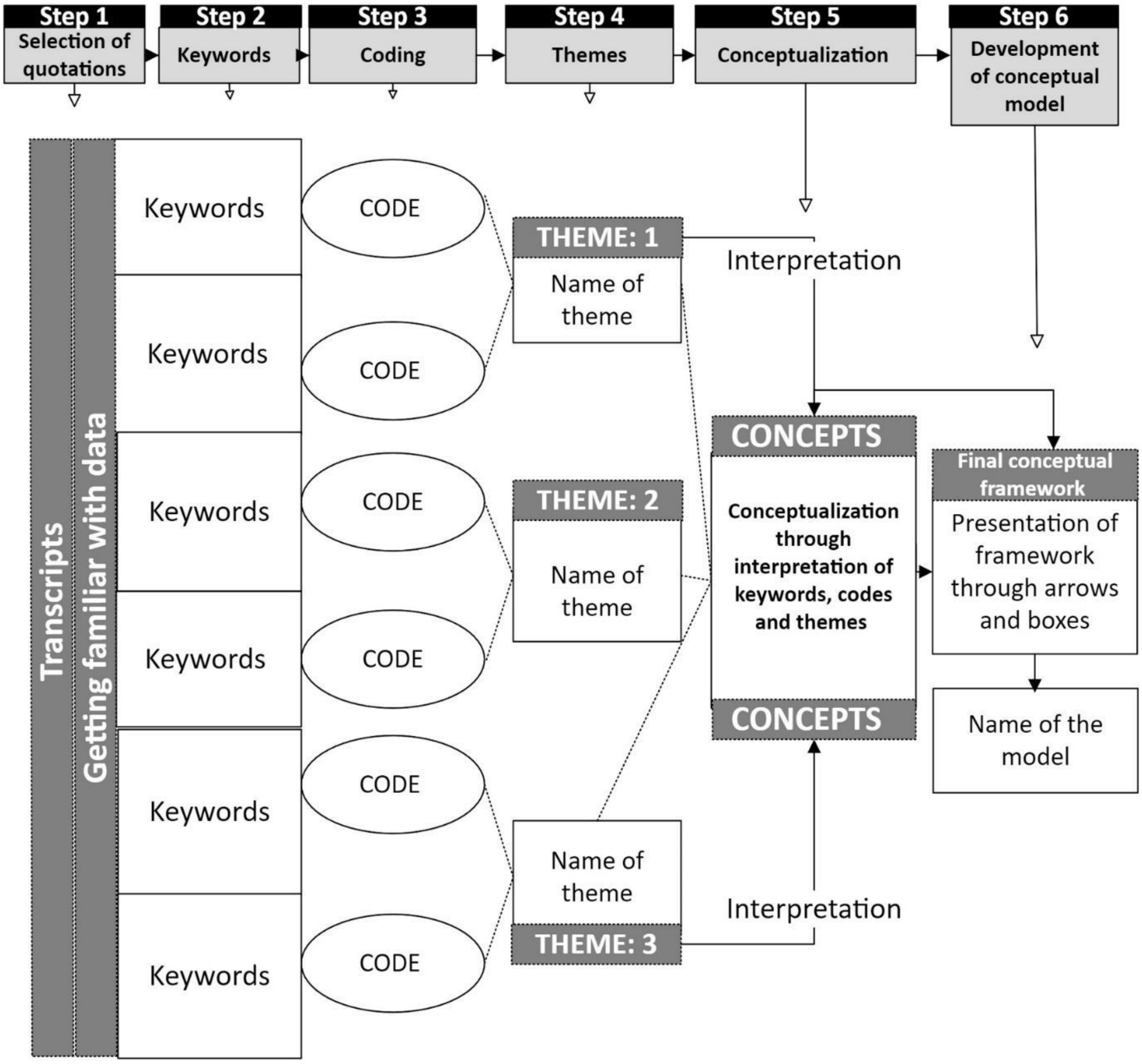

Figure 2.2 - A systematic thematic analysis process: A novel six-step process for conceptual model development in qualitative research.

Source: Naeem et al. (2023)

To explore complex phenomena and gain insight into individuals' experiences, perspectives, and behaviors based on the research questions, thematic analysis was deemed suitable for analyzing all the information generated from the interview data. Table 2.1 shows an example of the thematic analysis process, based on the steps proposed by Naeem et al. (2023), conducted over the data acquired from the interviews, from the quotations until reaching the final theme on the development of a conceptual model. Moreover, the conceptual models from the thematic analysis were used to create a conceptual framework, designed to guide the data analysis. The final conceptual framework can be seen in Figure 2.3.

Table 2.1 - Example of thematic analysis process from quotations to the development of a conceptual model. Source: Author

Quotations	Keywords	Coding	Themes	Conceptua-lization	Development of conceptual model
The EU just released a new regulation on August 2023	EU new regulation	EU Battery regulation	Regulation unfamiliarity	Legislations / Regulations in place	**Regulatory and policy frameworks**
We need to understand if it is necessary to have temperature control at the warehouse	EU new regulation				
What is the role of the new "battery passport" to the operation we are planning	EU new regulation				
Each country may have a different restriction regarding the transportation of 2nd life batteries	Local regulations	Country specific regulations			
Different areas are not completely integrated or updated for executing processes following new regulations	Areas' integration	Country specific regulations	Regulation knowledge		
New regulations may be implemented in the near future	New regulations implementation				
2nd life batteries may be considered waste and impose more challenges to transport it	LIB waste regulatory challenge	LIB waste regulation	Regulation barrier	Business regulatory viability	
New EU regulation imposes future recovery targets for recycling that may hinder the option to recover/repurpose EVBs	Recycling recovery targets	LIB recycling regulation			
Many players in the supply chain are not ready to follow the regulations in place	Players not ready to adopt regulations	Regulation readiness	Regulation adoption		
Some of the new EU regulations may narrow the options of transportation between countries	Regulations narrowing options				
Other countries, like India, already have a regulation in place very similar to EU	Local regulations	Country specific regulations	Regulation opportunity	Business regulatory opportunity	
Brazil, a country that Volvo have operations, have not yet defined many of the restrictions that EU did	Local regulations				
By applying a standard process, Volvo can get ahead of other companies in countries that still don't have strict regulations, but plan to have in the future	Volvo standard processes	Volvo internal standards	Regulation driver		
Volvo group have already updated its internal flows for the new EU regulation	Internal flows readiness				

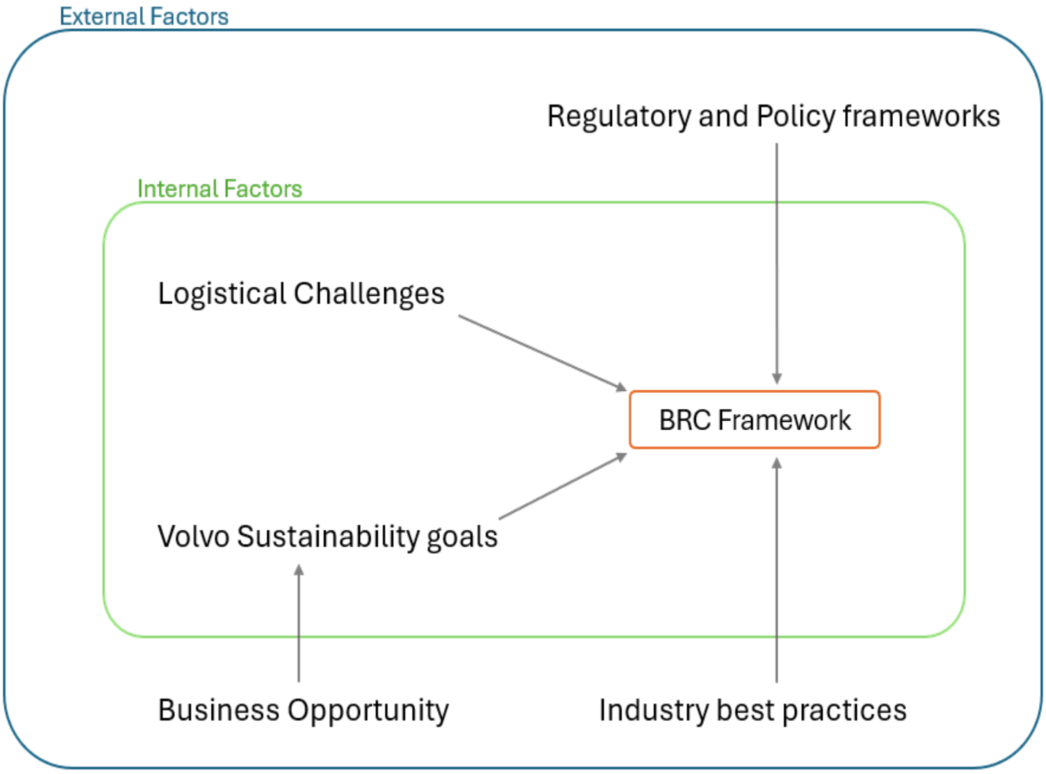

Figure 2.3 - Conceptual Framework.

Source: Author

2.4 Research Quality

Research quality is a multi-faceted concept that ensures the integrity and applicability of a study's findings (Descombe, 2010). This thesis research follows the concepts presented by Halldórsson and Aastrup (2003), which advocate for incorporating qualitative methods and alternative criteria for judging research quality, alongside traditional quantitative approaches. The authors state that by embracing multi-paradigmatic research efforts and qualitative approaches, logistics researchers can enhance the depth and richness of their studies, addressing the evolving demands of the discipline. Therefore, the four dimensions presented by Halldórsson and Aastrup (2003) will be used to guide the research quality of this text, namely credibility, transferability, dependability, and confirmability. These dimensions will be further elaborated below and will be linked to the strategies used by the author to align them throughout the thesis work, summarized in Table 2.2.

Table 2.2 - Research quality criteria and their contribution to this study

Source: Author

Quality criterion	Description	Methodological choices
Credibility	Internal validity of research findings	- Using different data sources for triangulation - Cross-checking information between different interviewees - Interviews validation
Transferability	Generalizability of research findings to other contexts and settings	- Mix of multiple and single case study methodology - Follow up of multiple factors leading to the result
Dependability	Reliability and stability of research results	- Complete methodological description in Chapter 2 - Openness about assumptions and limitations
Confirmability	Objectivity and neutrality of research outcomes	- Semi-structured interviews - Rigorous case descriptions - Recorded interviews - Extensive notetaking of interviews

Credibility

This research component refers to the trustworthiness of the research findings. According to Halldórsson and Aastrup (2003), credible research is rooted in robust methodology, including sound data collection and analysis techniques. It involves transparently documenting the research process to allow for replication by other researchers, ensuring that the findings are reliable and trustworthy. This study used a triangulation strategy to use data from different sources, both for the literature review, documentation exploration and interviews. The same information was checked on different sources and different interviewees were presented the same aspects of a problematic for them to provide their view. Also, it was possible to make follow-up questions and clarifications to the information on specific and technical aspects due to the close participation of the company in the case study.

Transferability

According to Descombe (2010), transferability assesses the extent to which research findings can be applied or transferred to other contexts or settings beyond the original study. High transferability implies that the results are applicable to similar populations, situations, or settings, enhancing the generalizability of the findings (Halldórsson and Aastrup, 2003). The results of this thesis are a combination of a single and multiple case study, which boosts the possibility of identifying aspects that are important for the generalization of concepts and are therefore explored in multiple contexts. Moreover, the empirical analysis performed in this thesis was methodically followed to ensure its relevance under the academic perspective and to create a result grounded on facts.

Dependability

Dependability refers to the consistency and stability of the research findings over time and across different conditions. Halldórsson and Aastrup (2003) states that a dependable study is one in which the results can be replicated or confirmed under similar conditions. This study carries a detailed description of the research methodology and a description of the participants' economical and strategical context, enabling the possibility for a peer review of the methodology robustness and the relevance of the findings in this text. Additionally, all the assumptions and limitations of the study are clearly described in the text, followed to which possible disadvantages they may cause.

Confirmability

Confirmability relates to the objectivity and neutrality of the research findings, indicating that the data collected, and interpretations made are not overly influenced by the researcher's biases or preconceptions (Halldórsson and Aastrup, 2003). Descombe (2010) underline that to enhance this research quality criterion, it is necessary to employ systematic and transparent data collection and analysis procedures, minimize researcher bias through reflexivity of data sources, and document any potential biases or conflicts of interest that may have influenced the research process. This thesis chose to perform semi-structured interviews, which, according to Kallio et al. (2016), have the advantage to reduce researcher bias when compared to a structured format. Additionally, the interview guide used for data collection was presented in its integral form, and their construction is backed by the information described in the text. Also, the companies participating in the study are described based on a combination of facts acquired in the interviews and public information. Finally, upon previous authorization of participants, all the interviews were recorded and extensive complementary notetaking was done to ensure quality of information and a reliable source of consultation.

2.5 Scope and Limitations

As can be seen in the research questions outlined in section 1.4, the geographical scope for the applications proposed in this study has been limited to the EU. Furthermore, instead of selecting a few specific automotive companies to participate in the interviews for data collection, this research explores business in several fields of EVBs second life solutions, thus accepting a potential loss in depth of the study for a gain in breadth.

The selection of the EU as scope is justified because it is the main market for EVs of Volvo Group's brands and the preferred geographical location for the implementation of the group's first BRC. Moreover, Volvo Group have a very strong logistical network in the European continent, with their main spare parts located in Ghent, Belgium, and Lyon, France, both responsible for the resupplying of spare parts to the rest of the world, alongside their main EV production plants being in Skövde, Sweden and Ghent, Belgium. The focus on all business fields related to the solutions for second life of EVBS is motivated by the fact that no consensus exists among academia or industry yet as to whether one specific area is the most beneficial from an environmental or economic perspective. Hence, this research investigates the different possibilities of both automotive and solutions providers regarding the life cycle management of EVBs.

Moreover, the reliability of results for the deployed activities within the reverse logistics of EVBs and the capabilities of a BRC on shipping, sorting, cleaning, charging / discharging, testing and storing could have been improved by increasing the number of interviews with representatives from even more companies, especially bigger players in the industry. The availability of such, however, was limited as the author was dependent on their willingness to cooperate. While fifteen companies were contacted, only the given six agreed to an interview. Hence, it is unlikely to expect that they would have been able to provide several interview partners. Lastly, it is also possible to highlight that the terminology of CE activities, as it will be introduced in section 3.1, and BRC capabilities, as it will be introduced in section 3.4, were not clearly distinguished amongst interviewees. Even though the author tried to define the terms as thoroughly as possible and ask clarifying questions, sometimes it was not clear which activity they were referring to.

2.6 Ethical approach

This project has received support from Volvo Group, a Swedish automotive company, under the scope of its subsidiary Volvo Energy. Volvo Energy provided financial backing and a workspace for the student's research in Gothenburg, Sweden. Additionally, they facilitated connections with various internal and external partners and stakeholders for data collection. The research topic and focus were collaboratively developed with Volvo Group and Volvo Energy, aligning with a transdisciplinary approach. However, it is important to note that the analysis and findings remained uninfluenced by this collaboration, ensuring the integrity of the research.

The ethical considerations surrounding the research are centered on the interview process and data collection. All interviewees participated voluntarily, with no distinction or preference regarding gender or race, and were provided written information detailing the research goals, collaboration with Volvo Group, and the intended use of the gathered information prior to the interviews. Consent was sought from interviewees to record the interviews and to include their name and position within their organization in the publication. For those who preferred anonymity, their names and, at times, their company names were replaced. Furthermore, specific information and quotes from individuals within the thesis draft were shared with the respective interviewees for verification before publication. Lastly, the empirical data collected is stored electronically on the author's personal laptop and within the protected cloud system of the university, ensuring confidentiality and security.

3 Literature Review

The literature review provides an overview of the concept of Circular Economy in section 3.1 and how the automotive sector for light and heavy-duty electrical vehicles is approaching this strategy in section 3.2. Then, section 3.3 focus is on the product of EVBs by presenting existing circular economy strategies and practices, followed by a discussion of the capabilities for the implementation of a battery return center in section 3.4. Lastly, section 3.5 explores the challenges for a battery return center implementation and scalability.

3.1 Circular Economy

The circular economy (CE) is an economic approach aimed at promoting sustainability and environmental protection by reducing waste and efficiently using resources through strategies such as recycling, reusing, repairing, and remanufacturing. It aims to balance economic development with environmental and resource protection, reducing the demand for raw materials and integrating the recovery, recycling, and reuse of resources into the production process (Jones & Comfort, 2017; Nikanorova & Stankevičienė, 2020). The CE is founded on environmental, economic, and social dimensions, ensuring sustainable development at every stage of product creation, transformation, and conversion, thus establishing a closed-loop economy (Stahel, 2016).

This economic model bluntly contrasts with the traditional linear economy, which follows a "take, make, and dispose" pattern, and is characterized by waste elimination through design, respect for the social, economic, and natural environment, and resource-conscious business conduct (Sariatli, 2017). Therefore, there is a clear environmental appeal to CE, since the traditional production flow of extract and process raw materials can have substantial environmental impact. The basic re-utilization of products by recycling, reusing, repairing, or remanufacturing generates less, but non-negligible, environmental damage (Zink & Geyer, 2017). To the degree that this secondary use of the material and products actually prevents the primary production of new items, and the environmental benefit is the distinction amongst the inherent impacts of reprocessing and what is evaded by not performing a primary production (Zink & Geyer, 2017).

The definition of CE can be very broad, but it is possible to highlight that an ultimate goal for all the concepts that intertwine is to achieve sustainability. That is supported by dimensions that interfaces on different areas of business performance, defined as social, environmental, and economical (Ellen MacArthur Foundation, 2015; Meidl, 2021). A framework of the objectives of the CE can be seen in Figure 3.1.

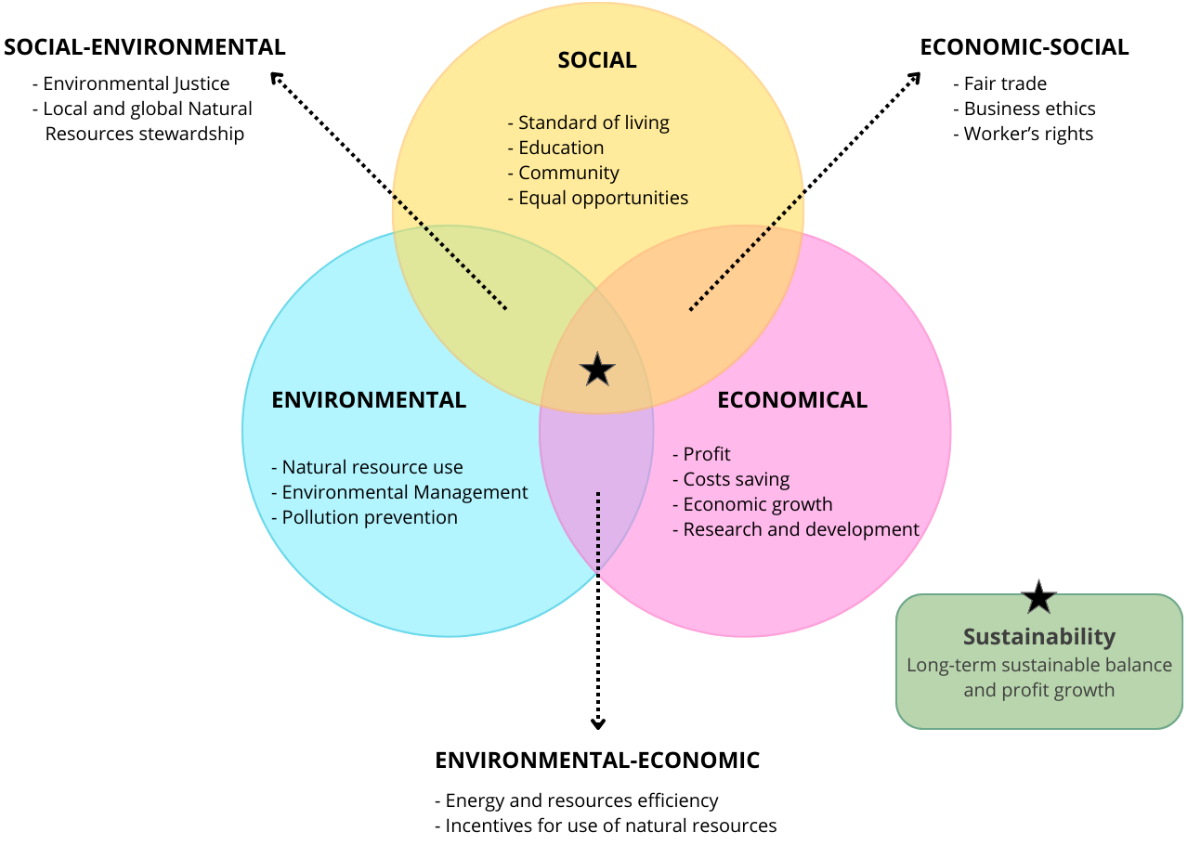

Figure 3.1 - CE Objectives.

Source: adapted from Meidl (2021)

The technical cycle within the framework of the circular economy entails implementing sustainable practices and embracing closed-loop systems to reduce resource usage and environmental impact (Ellen MacArthur Foundation, 2013). This transformation necessitates combining diverse characteristics and insights from various concepts centered around closed-loop principles, thereby restructuring processes throughout the product lifecycle (Geissdoerfer et al., 2017)

This process seeks to harmonize economic development with environmental and resource conservation objectives by reducing the need for raw material inputs and natural resources, while also recovering, recycling, and reusing these inputs and resources within the production process (Jones & Comfort, 2017). The principles of the circular economy originate from the elimination of waste and pollution, the prolongation of the utility of goods and materials, and the regeneration of natural systems. These principles hold promise for addressing environmental challenges like climate change, waste management, and pollution (Dijmarescu, 2022)

While the circular economy offers a promising path towards sustainability, its connection is not always directly linked (Geissdoerfer et al., 2017). Potential downsides like "rebound effects"[1], could negate the initial environmental benefits of circular products or services (Meidl, 2021; Zink & Geyer, 2017). Therefore, assessing the full impact of CE strategies through methods like material flow accounting and life cycle assessments is crucial to identify any unintended consequences (Geissdoerfer et al., 2017; Manavalan & Jayakrishna, 2019). To truly contribute to sustainability, the implementation of CE strategies must consider their overall impact, not just their economic value. Advocates to the CE transition, like The Ellen MacArthur Foundation, recommended prioritizing activities that maximize product lifespan and value retention, known as "inner loop" or value-retention strategies (Ellen MacArthur Foundation, 2015). These activities, like sharing, repair, reuse, and remanufacture, conserve the most embedded materials, energy, and labor (Ellen MacArthur Foundation, 2015). Recycling should only be considered when these options are exhausted, and materials should then be cycled within the "outer loop" as much as possible (Geissdoerfer et al., 2020). This concept is further visualized in Figure 3.2.

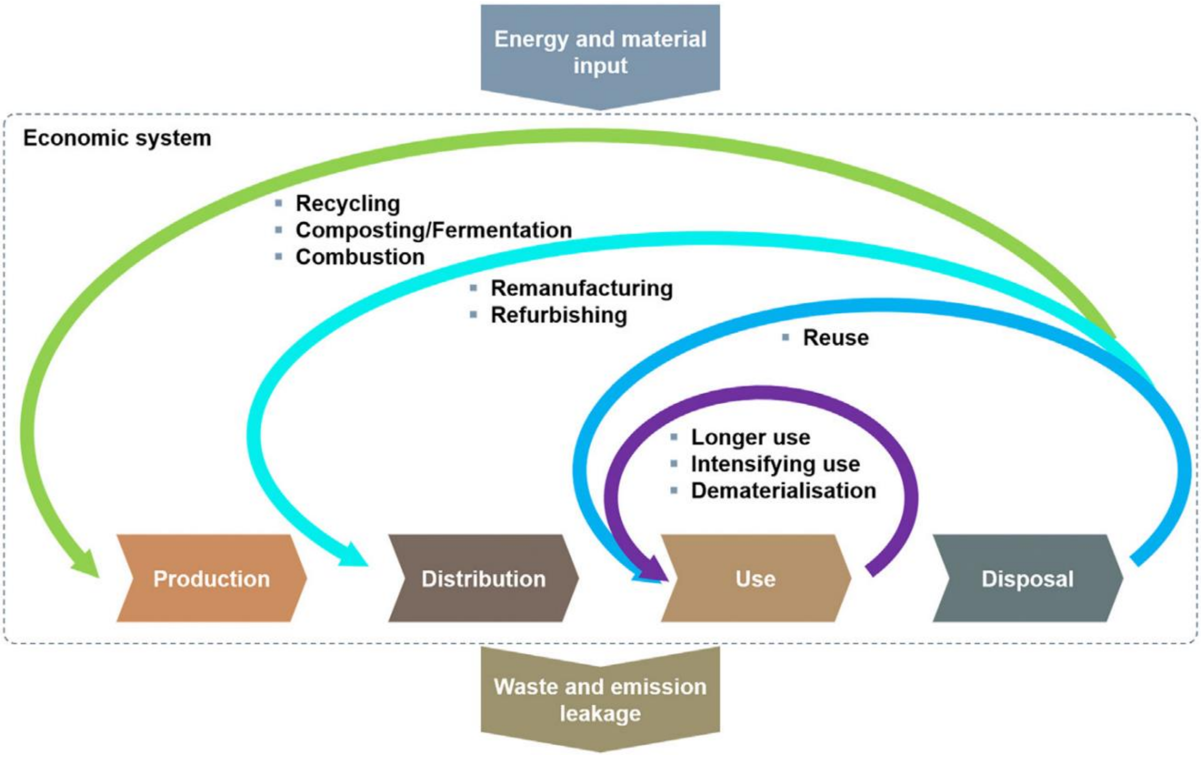

Figure 3.2 - Cycles of CE.

Source: Geissdoerfer et al. (2020)

Many definitions of the circular economy overemphasize recycling, neglecting the crucial need for a fundamental system change to achieve it (Manavalan & Jayakrishna, 2019). From a sustainability perspective, CE prioritizes inner loop strategies within its technical cycle, aiming to improve resource efficiency beyond initial production (Ellen MacArthur Foundation, 2013). However, the boundaries between inner and outer loop activities are often unclear, leading to confusion in both research and industry communication. To address this, Table 3.1 outlines the most common definitions of these terms.

---

[1] An umbrella term for a sort of economic means that decrease the energy savings from enhanced energy efficiency (Castro et al., 2022)

Table 3.1 - Definitions of CE activities

Sources: Ellen MacArthur Foundation (2013); Lüdeke-Freund et. al (2019); Morseletto (2020); Blomsma et. al (2919)

Term	User	Definition
Repair	First user	Increases a product's lifespan during its initial use through minor repairs. These repairs, performed by manufacturers or professional service providers, restore or maintain the product's functionality.
Reuse	Second hand	Extends a product or part's life cycle by giving it a second life with a new user. This involves using the product for its original purpose with minimal modification or upgrades.
Refurbish	Second hand	Gives a product a second life by replacing key components. This revitalizes its functionality and ensures acceptable performance for a new user.
Remanufacture	Second hand	Grants a product a new lease on life through extensive refurbishment. This involves replacing key components and restoring the product to a near-new condition, offering comparable performance to a new product for a second-hand user.
Repurpose	Second hand in other application	Extends the life of a product by giving it a new purpose. This involves using it for a different purpose than its original design, effectively giving it a second life, cascaded use, or second use.
Recycle	-	Creates closed material loops by recovering raw materials from products and reintroducing them into new product creation. These recovered materials can be used to create products with lower (downcycling or open-loop), similar (closed-loop), or even higher (upcycling) quality and functionality compared to the original product.

In this work, the focus lies on the micro-level of such an economic system addressing how businesses can implement and operationalize the principles of the CE in their activities for the EOL of EVBs. Thus, the upcoming chapters focuses on developing knowledge around the strategies, capabilities and challenges for a battery return center design and implementation.

3.2 Light and Heavy-Duty Electric vehicles business

The idea behind the development of EVs is not new, on the contrary, in 1915 Thomas Edson launched an e-bus that was the first EV used for public transportation (Bergsson, 2005). However, the heavy weight of the battery and the lack of autonomy were big limitations for this first generation of EV and, even more recently, the lack of infrastructure in most cities made the hybrid between internal combustion and electric vehicles more popular than the fully EV alternative (Arora et al., 2021).

Road freight transportation is on a slow, but steady, increase since the year of 2012 and continues to be the main mode of transportation in the European Union, representing 77.3% of total inland freight transport in 2021 (Statista Research Department, 2023). At the same time, governments are also changing regulations to encourage the transition to cleaner solutions for the greenhouse gas emissions and air pollution problems (European Commission, 2019; Tankou et al., 2023; Sagaria et al., 2021). This pattern has been leading the automotive industry to look for alternative technologies for the powertrain of light and heavy-duty vehicles, such as battery EVs, PHEVs, and fuel cell electric vehicles (FCEVs) (Cunanan et al., 2021 Sagaria et al., 2021).

The electrification of the transportation sector is currently on the rise and the expectation for the future is that this tendency will grow quite sharply in the upcoming years (Zhang et al., 2023). The shift towards electric transportation has also caused a favorable cycle of reinforcement and a willingness to increase the acceptance level of alternatives to diesel (Muratori et al. 2021; Bae et al., 2022). Progress in battery technology, driven by the widespread of EVs adoption and enabled by powerful positive feedback mechanisms, is resulting in an expanded scale and experience, ongoing research and development, consumer familiarity with technology, and complementary resources such as charging infrastructure (Struben & Sterman, 2008; Muratori et al. 2021; Vijayagopal & Rousseau, 2021). This is leading towards an exponential growth on the associated components, like lithium-ion batteries (LIBs), that are essential for the development of this industry (Slattery et al., 2021). According to the International Council on Clean Transportation (ICCT) the increasing sales of light and heavy-duty BEVs and PHEVs, which can be seen in Figure 3.3, will generate a global amount of around 1.2 million batteries in their end of life in 2030, rising to 14 million in 2040 and reaching the level of 50 million by 2050 (Tankou et al., 2023).

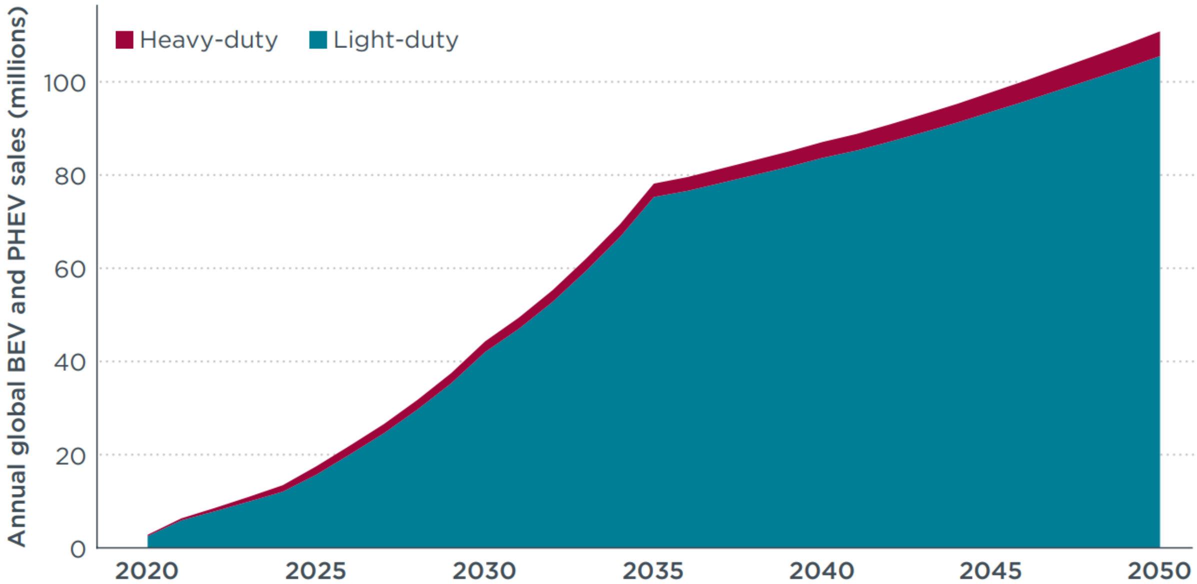

Figure 3.3 - Projected annual global new light-duty and heavy-duty BEV and PHEV sales.

Source: Tankou et al. (2023)

3.2.1 Economic drivers

The economic drivers for the adoption of LDEVs and HDEVs are crucial factors that influence fleet operators and decision-makers to consider transitioning to electric trucks. For example, one of the primary economic drivers for HDEV adoption is the potential for cost savings over the vehicle's lifetime, expressed as Total Cost of Ownership (TCO), and nowadays the upfront cost of electric trucks may be higher than diesel counterparts, however, lower operating and maintenance costs can lead to significant savings in the long run (Morrison et al., 2018).

Another relevant drive is the availability of spare parts in the aftermarket supply. Fleet operators rely intensively on this availability in order to run their operations and it will be very hard to scale the HDEVs business if a spare parts bottleneck is not addressed (Naor et al., 2021). That is why several OEMs are developing models and investing to solve the remaining technical challenges specific to HDEVs and, as new models are launched for operation, this network shall intensify and reach a feasible state for big fleet owners run their entire operations based on electric powertrains only (Heid et al., 2017).

Moreover, it is also possible to consider that as sustainability and environmental consciousness become increasingly important to consumers and businesses, adopting electric trucks can enhance a fleet operator's brand image and market competitiveness (Sugihara et al., 2023). Therefore, meeting the growing demand for eco-friendly transportation solutions can generate new business opportunities and partnerships.

3.2.2 Environmental drivers

The appeal on the environmental impact and long-term sustainability are also factors that are boosting the present and future demand for road transportation electric powertrains, as their internal combustion counterparts still produce high emissions and fuel consumption on trucks, buses, and other heavy-duty vehicles (Mallon et al., 2017). There are several indicators in place that highlight the advantages on CO_2 footprint and energy consumption rates, especially when considering the use of batteries in a circular economy, extending its usable time and recycling crucial components at the very end (Lee et al., 2013; Sato et al., 2022). Hence, medium and heavy-duty battery electric trucks are expected to play a key role in mitigating greenhouse gas emissions from road freight transportation (Samet et al., 2021).

Not all drivers, however, are so well known for air pollution. Several articles are concluding that electric trucks operate quietly compared to diesel trucks, resulting in reduced noise pollution in urban and residential areas (Tsoi et al., 2023; Reis, 2019; Moll et al., 2020). This can lead to a more pleasant and peaceful environment for communities along transportation routes inside cities but also in rural areas (Sugihara et al., 2023). Another factor that can be highlighted is that EVs rely on electricity as a power source, which can be generated from renewable energy sources such as solar, wind, or hydroelectric power. By using clean energy to charge electric trucks, fleet operators can contribute to resource conservation and reduce reliance on finite fossil fuels (Forrest et al., 2023).

Companies are trying to boost their implementation of EVs by extending their strategies to include customers, suppliers and partners in the equation. Volvo Group, for example, is setting incentive programs to make EVs a more viable option, from a TCO perspective, so their customers have a better deal by renovating their fleets of trucks, buses, and construction equipment to electrical solutions (Volvo Group, 2024). Volvo Group’s last sustainability report set their ambition to reach net-zero greenhouse gas emissions by 2040, as seen in Figure 3.4.

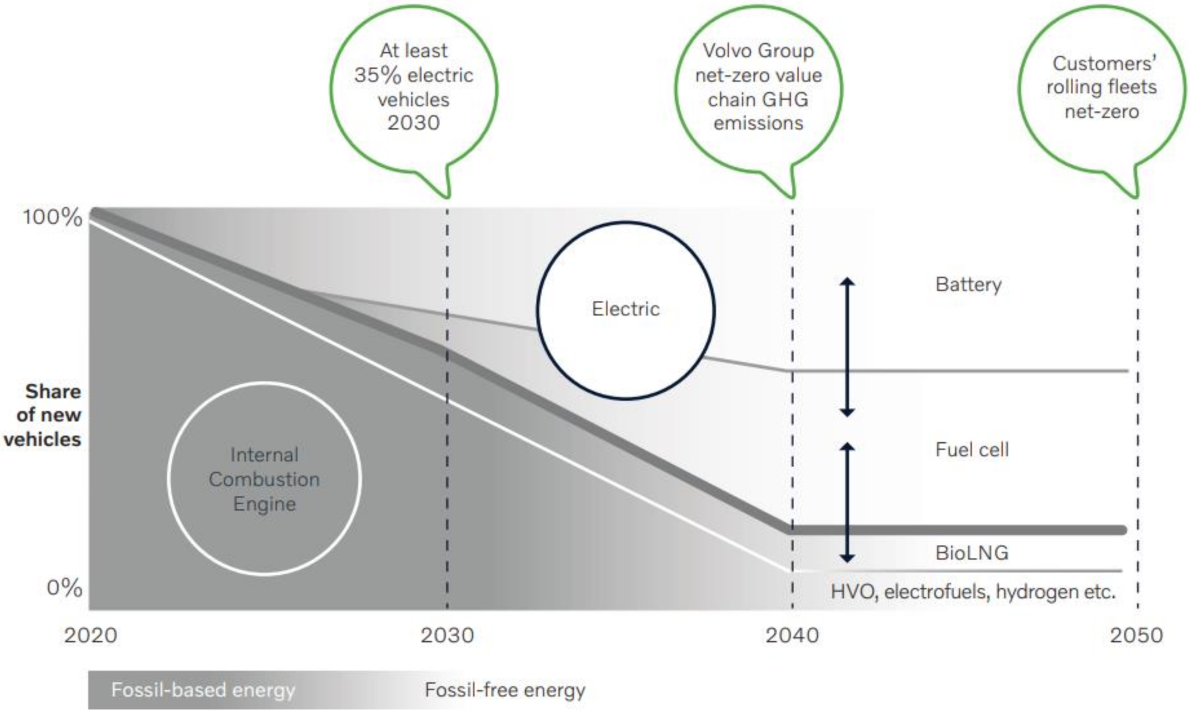

Figure 3.4 - Volvo Group's path to decarbonization.

Source: Volvo Group (2024)

3.2.3 Governmental drivers

Governments worldwide are implementing stringent regulations and emission standards to reduce greenhouse gas emissions, improve air quality, and combat climate change. The 'European Climate Law' (European Commission, 2023) and 'The long-term strategy of the United States' (U.S. Department of State, 2021) are two examples of how governments are pushing their communities towards climate-neutral zero greenhouse gas emissions, and the adoption of electric trucks is stated as a driver for the transition towards cleaner transportation technologies.

Beyond laws and regulations, governments often offer a range of financial incentives, such as rebates, grants, and tax credits to encourage the adoption of electric vehicles, including light and heavy-duty trucks. These incentives help offset the higher upfront costs of electric trucks, making them more economically viable for fleet operators (Sugihara et al., 2023). However, it is possible to argue that LDEVs and HDEVs are not yet good substitutes due to some degree of limited range and lesser available infrastructure for charging (Giuliano et al., 2021). Hence, government agencies also try to drive this change, leading by example through their own procurement policies. By incorporating electric trucks into their fleets and investing in charging stations inside cities, governments create a market demand for electric vehicles and demonstrate the feasibility and benefits of electrification to other fleet operators. (Fenton & Kailas, 2021)

Lastly, there are also international agreements that play an important role in the direction that local regulations are shaped. The Paris Agreement, signed in 2015, has strong guidelines in shaping national commitments towards achieving net-zero emissions by 2050 (Rogelj et al., 2021). The agreement sets ambitious goals for reducing carbon emissions, which in turn drives the transition to renewable energy technologies, including EVBs (Clark et al., 2021). In order to be in line to the agreement targets, governments worldwide have initiated programs to accelerate the adoption of EVs and the manufacturing of LIBs is also expecting potential reductions in emissions related to battery production, which is projected to decrease significantly by 2030 and 2050 if global manufacturing aligns with the decarbonization goals (Chinthakunta et al., 2019; Morfeldt et al., 2022).

These economic drivers, along with advancements in technology and infrastructure, play a significant role in accelerating the adoption of EVs for road transportation in the commercial area.

3.3 Electrical Vehicles strategies for End-of-Life batteries

The increasing demand in LIBs is naturally creating a cascade effect on the demand for raw materials, however, components like lithium and cobalt have a significant negative impact for the environment in their extraction process, which calls for alternatives to extend as much as possible the usable life of these minerals (Rey et at., 2021). Additionally, there is a limited supply of these critical materials as described by the International Energy Agency (2021) (e.g., nickel, platinum, lithium, and cobalt). This has an economic and geopolitical effect that increases the importance of actions reusing these materials to the maximum to reduce the dependency of virgin supply (Zeng et al., 2022).

The implementation of circular economy principles can significantly reduce the demand for primary materials in several ways alongside the supply chain (Dunn et al., 2021). Some researchers argue, however, that this shift should already be in place, as the work done by Baars et al. (2020) highlights that it is an immediate need that government and businesses adopt more ambitious circular economy strategies, otherwise there is going to be an imminent shortage in the supply of several rare metals in the upcoming years. Yet, the success of circular economy strategies depends on the demand, use, and retirement patterns of EVBs over time, as well as the evolution of LIBs chemistry (Dunn et al., 2021). Nonetheless, all these challenges seem to be pushing the industry development and the scientific advancements towards a stage that considers the processes at the EOL of EVBs as relevant as the development of new products (Meegoda et al., 2022; Zeng et al., 2022; Tankou et al. 2023).

EOL EVBs are simply LIBs that have reached the point where they can no longer effectively power the vehicle up to the standards that are expected on a commercial level (Muratori et al., 2021). Like all batteries, the performance of EVBs degrades over time due to factors such as charge-discharge cycles, temperature variations, and usage patterns. However, this doesn't necessarily mean they're completely dead, but that their ability to hold a charge and provide sufficient range has degraded significantly, usually to around 70% to 80% of their original capacity (Canals Casals et al., 2017; Illa Font et al. 2023).

Despite an EVB no longer meeting the performance requirements for vehicle use, it often retains a significant portion of its capacity and can be repurposed for other applications (Canals Casals et al., 2017; Hossain et al., 2019). For instance, EOL EVBs find utility in stationary energy storage systems, such as grid energy storage, backup power for buildings, or integrating renewable energy sources (Muratori et al., 2021; Illa Font et al. 2023). Eventually, when an EVB can no longer be effectively repurposed or reused, it enters the recycling stage. Recycling involves disassembling the battery pack, recovering valuable materials such as lithium, cobalt, and nickel, and processing them for reuse in new batteries or other applications. This recycling process helps reduce environmental impact by minimizing the need for raw material extraction and decreasing the volume of waste sent to landfills (Rey et al., 2021; Muratori et al., 2021; Illa Font et al. 2023).

Several authors wrote in the near past about how linear the lifecycle of EVBs seemed to be, from assembly to disposal, and called for the necessity of a more circular approach to attain an economically sustainable industry (Olsson et al., 2018; Beaudet et al. 2020; Engel et al. 2019; Cusenza et al., 2019). More recently, however, this perspective seems to be shifted, and the academic works indicate that a CE strategy is the prime concept for doing business that all major players on industry are developing around (Albertsen et al., 2021; Börner et al., 2022; Nurdiawati & Agrawal, 2022). Additionally, many of these works propose frameworks to explain how the CE strategy is designed for the EVB life cycle, like the ones found in the works of Albertsen et al. (2021), Beaudet et al. (2020), Engel et al. (2019), Kurdve et al. (2019), and Börner et al. (2022). For the development proposed in this text, those ideas were combined and simplified in the diagram found in Figure 3.5.

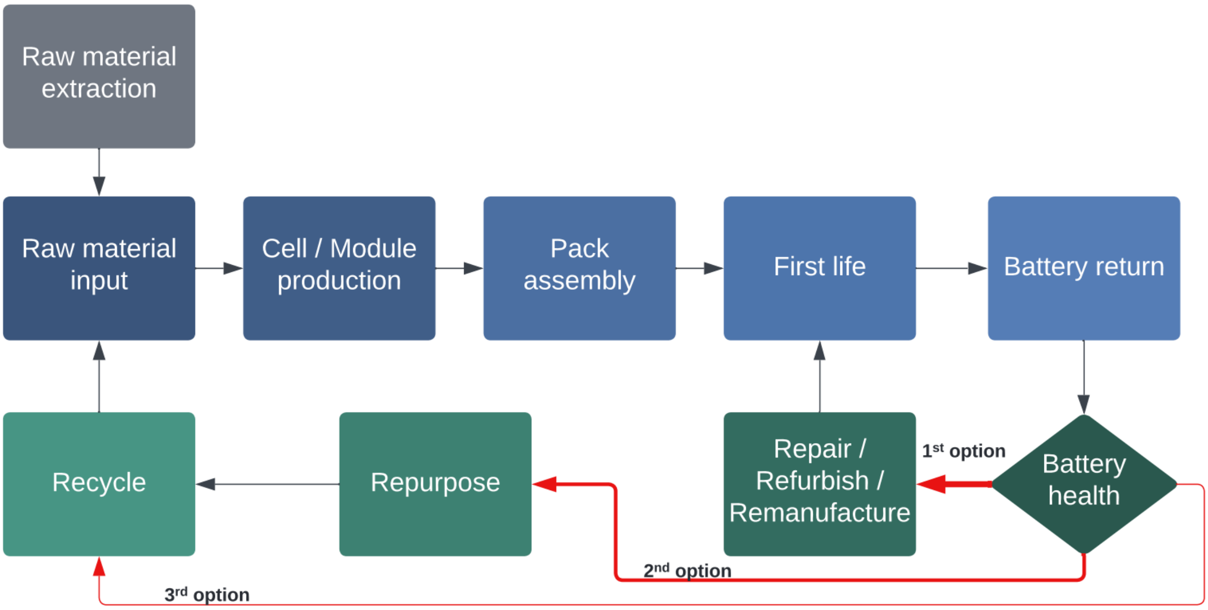

Figure 3.5 - CE Strategies for EVBs.

Source: Author

A crucial point in the process is the decision on which path the returned battery should follow to begin its second life. There are several technical aspects based on the battery health status to determine to which application it is more suitable for, and different models and digital applications can be found to perform the tests to acquire this information, as described, for example by the works of Chai et al. (2021), Baumann et al. (2018) and Haram et al. (2023). However, it is possible to expand this perspective to consider a more strategic and economic level of decision, as proposed by Zhu et al. (2021), according to which "*the determination of the threshold value should take economic feasibility and the condition of the rest of the vehicle into account, for example, the market demands of second-life battery performance (e.g., frequency modulation is much less demanding than peak shaving) and the potential* *profitability of prematurely retiring the batteries. To sum up, the point at which batteries should retire from an EV should be re-considered by analyzing the trade-offs between demand and supply in the new revolving economy system*" (2021, p.2). Taking this into consideration, a broader approach for this problem should consider both a technical aspect, based on predefined standards, and how companies can have a better use of their assets and make this process to increase their economic performance.

The literature also indicates that there is a preference for the options in the second life of EVBs when considering economical aspects, such as total profit with investment, payback year and return rate, which will influence the decision of stakeholders on where to invest and how the logistics return flow should be designed (Vu et al., 2020). Given the current processes, batteries compositions, and market availability, refurbishing and remanufacturing the batteries seems to be the options that provides better economic value, as they will be sent back to the first life application with high value retainment; followed by repurposing, which may not be as economic valuable but have the best payback time over investment; and the last option remains as recycling, although some companies were able to build profitable operations, it still require move technological improvements to increase the recovery efficiency (Vu et al., 2020; Zhu et al. 2021; Fan et al., 2020; Horesh et al., 2021).

3.3.1 Repair, Refurbish, Remanufacture

There is a very thin line that differentiates repair, refurbish and remanufacture of EVBs in relation to the processes and expected outcomes for both companies and customers. Even some academic works will try to discuss and clarify the difference between these terms (Gharfalkar et al., 2016; Russel & Nasr, 2023), but the main message is the importance on the re-usability of the materials to nurture the circular economy, rather than having a clear definition of each terminology. Hence, for the purpose of this work, they will be all grouped and described under the same macro-processes and definitions as the 'remanufacturing' process. Still, Table 3.1 can be referred to exemplify the unique characteristics of each terminology.

As an initial observation, there is an increased attention from industry and academic research to the remanufacturing of EVBs due to the current increase in sales for electrical and hybrid vehicles, as well as the forecasted surge in retired power batteries in consequence of the increasing use of these vehicles (Meng et al., 2022). The remanufacture of EVBs is a critical aspect of the circular economy principles for extending the useful life of the materials for several more years, but that requires a complex process to achieve a battery that is almost as good as a new one, and it involves steps such as diagnosis, partial disassembly, replacement of damaged cells or modules, and reassembly into new battery packs (Chen et al., 2019).

The new European Union regulation concerning EVBs and waste EVBs, in place since august 2023, describes the remanufacturing of EVBs as follows: "*As regards used batteries, remanufacturing has the objective of restoring the original performance of a battery. In that sense remanufacturing can be seen as an extreme case of re-use entailing the disassembly and evaluation of the cells and modules of the battery and the replacement of a certain amount of these cells and modules. In order to differentiate remanufacturing from mere re-use, the restoration of the battery capacity to at least 90 % of the original rated battery capacity should be considered to be remanufacturing and necessitates the application of a specific regime*" (European Union, 2023, p. 4). This sets some base grounds that companies should follow in order to commercialize in the second life market for EVBs and have the positive effect of ensuring a minimum quality level for the customers.

There are some solid benefits advocating for the increase of the remanufacturing process. For example, the study done by Richa et al., (2015) highlights that the reuse of batteries can offset the environmental impact of manufacturing new batteries by extending the lifespan of existing batteries, thus contributing to environmental sustainability. Olsson et al., (2018), adds that the environmental sustainability benefits of EVB remanufacturing are further emphasized by the complementary nature of reuse and recycling processes. Additionally, they also suggest that the largest sustainability benefit can be achieved if EVBs are first reused and then recycled.

On a more economic perspective, Gu et al., (2018) performed a comparison between selling and leasing for new and remanufactured products in the EV industry, with their findings indicating the various possibilities for managing post-vehicle application batteries, including remanufacturing for intended reuse in vehicles, repurposing for non-vehicle applications, and recycling, creating a combination that was able to optimize total profits.

Many companies are advertising initiatives that have a focus on the remanufacturing of EVBs, for example, Nissan is trying to create an EV 'ecosystem' based on the circularity of their own batteries and has established a facility in Japan to remanufacture EVBs for Leaf owners, offering re-buying policies and cheaper remanufactured batteries as a replacement option; such investments can be seen as an indicator for a growing market for remanufactured batteries (Hua et al., 2020).

However, some researchers recommend that it is still necessary to create more measures to endorse markets for remanufactured EVBs and provides business with more marketing options to accelerate their adoption by the public, and, at the same time, increasing the maturity of local dealership networks (Chinen et al., 2022; Rönkkö et al., 2024).

3.3.2 Repurpose

The repurposing of EVBs is a crucial aspect of sustainable battery management. In the context of second-life applications, such as stationary energy storage, the repurposing of EVBs does not only provide economic benefits but also contributes to the sustainability efforts, by extending the useful life of these batteries and expanding its range of possible applications (Kumar et al., 2023).

Likewise remanufacturing, the new European Union regulation concerning EVBs and waste EVBs, also have a description for the repurposing of EVBs: "*It should be possible for industrial batteries and electric vehicle batteries that are no longer fit for the original purpose for which they were manufactured to be used for a different purpose as stationary energy storage batteries. A market for used industrial batteries and used electric vehicle batteries is emerging and in order to support the practical application of the waste hierarchy, specific rules should thus be established to allow responsible repurposing of used batteries while taking into account the precautionary principle and ensuring safety of use for end-users. Any such used battery should undergo an assessment of its state of health and available capacity to ascertain its suitability for a purpose other than its original purpose. Batteries that are found to be suitable for a purpose other than their original purpose should ideally be repurposed. In order to ensure uniform conditions for the implementation of requirements that waste industrial batteries,* *waste LMT batteries or waste electric vehicle batteries should fulfil to cease to be waste, implementing powers should be conferred on the Commission*" (European Union, 2023, p. 21). This section of the regulation specifies that all the EVBs should be designed in such a way that the repurposing after the end of the first life is possible and desired, given that the battery still has enough conditions for that.

The process for repurposing an EVB to have a new application in their second life will, ideally, not include any disassembly, however this can still be done if faulty cells should be replaced, which will be found after testing for degradation and failure (Meegoda et al., 2022). The process will also include packaging the batteries for second life, as well as adding electrical hardware, control, and safety systems (Catton et al., 2019). In a deeper level of discussion, some authors argue that dismantling down to cell level is not feasible from a technical or economic perspective (Catton et al., 2019; Canals Casals et al., 2017). Instead, it is suggested the use of the entire battery pack without refurbishing. Faulty EVBs, however, should undertake a module level examination to identify, select and change modules with similar features together, then a new battery pack for a second life application can be rebuilt (Song et al., 2022).

Typically, there is an emphasis on the necessity of employing advanced monitoring and testing techniques to discover the potential longevity of a battery pack, module, or cell (Thakur et al., 2012). Numerous studies delve into innovative approaches for cell monitoring through the Battery Management System (BMS), aiming to reduce the necessity of performing additional tests and readings on the battery after it was removed from the vehicle and enhance understanding of battery usage patterns to facilitate informed decisions regarding lifespan extension (Gabbar et al., 2021; Lauder et al., 2014).

The repurposing of EVBs offers several advantages that need to be carefully considered. Firstly, repurposing EVBs for second-life applications maximizes economic benefits by extending the useful lifetime of the batteries before recycling, thus reducing the overall cost of ownership (Iqbal et al., 2023). Secondly, repurposed EVBs can be utilized in stationary storage applications, providing peak shaving and load shifting capabilities, which contribute to grid balancing and energy management (Faria et al., 2014). Additionally, this process can also offer advantages such as voltage support, frequency regulation, and power quality when used as stationary batteries, showcasing their versatility in various applications (Guven et al., 2021).

Several studies have explored different aspects of repurposing EVBs, including technical feasibility, economic viability, and environmental benefits. For instance, research by Al-Alawi et al. (2022) evaluated the potential of repurposed EVBS for residential energy storage systems, highlighting the cost-effectiveness and environmental advantages compared to conventional storage solutions. Similarly, a study by Gür (2018) investigated the technical challenges and opportunities associated with repurposing EVBs for grid-scale energy storage, emphasizing the importance of standardization and system integration.

Moreover, initiatives by automotive manufacturers and energy companies demonstrate a growing interest in repurposing EVBs. Companies like Tesla and Nissan have launched programs to recycle and repurpose retired EVBs for various applications, including energy storage for homes and businesses (McDougall, 2023). Furthermore, collaborative efforts between industry stakeholders, policymakers, and researchers are essential for advancing repurposing technologies and establishing regulatory frameworks to support widespread adoption (Canals Casals et al., 2017). Lastly, despite obstacles such as economic, environmental, and regulatory factors, repurposed EVBs in second-life energy storage systems are viewed as a promising avenue for future development (Faessler, 2021).

3.3.3 Recycle

The recycling of EVBs is becoming increasingly important as the global adoption of electric vehicles continues to rise. EVBs are typically lithium-ion batteries, which contain valuable rare metals such as lithium, cobalt, nickel, and manganese, along with other materials already well known in the recycling universe, like aluminum and copper (Miao et al., 2022). Recycling offers a sustainable solution to manage EOL batteries, minimize environmental impact, and recover valuable materials for reuse in new battery manufacturing, reducing the demand for virgin resources and lowering the environmental footprint of battery manufacturing. (Kotak et al., 2021).

It is possible to identify a considerable number of studies that have investigated the aspects of EVB recycling, including technological advancements, economic viability, and environmental benefits. For instance, the research done by Tao et al. (2021) discuss on the findings regarding different methods (direct cathode recycling and hydrometallurgical recycling) for recycling high-performance lithium-ion batteries and arguing that direct cathode recycling emerges as a more environmentally favorable option compared to hydrometallurgical recycling, offering significant potential for reducing environmental impacts and promoting sustainability. Additionally, a study by Fan et al. (2020) evaluated the economic feasibility of recycling EVBs and identified opportunities to optimize recycling processes and enhance resource recovery.

Furthermore, the works of Beaudet et al. (2020) and Li (2022) explored the funding for innovation in recycling technology, as well as the academic participation, responsible for supporting pilot projects, and creating a favorable economic and regulatory environment, which are seem like essential steps to overcome challenges in large-scale EVB recycling. Besides, governments and industry stakeholders are increasingly recognizing the importance of battery recycling and implementing policies and incentives to promote sustainable practices. Initiatives such as the European Union's Battery Directive and the US Department of Energy's Battery Recycling Prize aim to support the development of recycling infrastructure and technologies (European Commission, 2023; U.S. Department of State, 2021). Moreover, partnerships between automotive manufacturers, battery producers, and recycling companies are fostering collaboration and innovation in the recycling supply chain.

Recycling EVBs has a direct benefit mix of economic and environmental perspectives. Firstly, it allows for the recovery of valuable metals, which helps secure the alternative materials supply chain and reduces dependence on exporting economies (Pražanová et al., 2022). Additionally, the reuse and recycling of retired batteries from EVs have been shown to have significant economic value and can contribute to reducing the environmental burden associated with battery disposal (Liu & Zhu, 2023). By reusing and recycling retired EVBs, it is possible to decrease the CO_2 emissions associated with mineral extraction and battery assembly, which can account for a substantial portion of the overall carbon footprint of EV production (Zhang et al., 2023).

In this context, much is said on increasing the efficiency of the recycling process for LIBs, and the new European Union regulation states that: "*The increased use of recovered raw materials* *would support the development of the circular economy and allow a more resource-efficient use of raw materials, while reducing Union dependency on raw materials from third countries. For batteries, this is particularly relevant for cobalt, lead, lithium and nickel. Therefore, it is necessary to promote the recovery of such materials from waste, by establishing a requirement for the level of recycled content in batteries using cobalt, lead, lithium and nickel in active materials. This Regulation should therefore set mandatory recycled content targets for cobalt, lead, lithium and nickel, which should be met by 2031. For cobalt, lithium and nickel, increased targets should be established by 2036. (...) . Battery manufacturing waste is likely to be the main source of secondary raw materials for battery manufacturing due to the increase in the production of batteries and should be subject to the same recycling processes as post-consumer waste. Therefore, battery manufacturing waste should be counted as part of the recycled content targets with the objective of accelerating the development of the necessary recycling infrastructure. However, by-products of battery manufacturing that are re-used in the production process, such as manufacturing scrap, do not constitute waste and should therefore not be counted as part of the recycled content targets."* (European Union, 2023, p. 6)

Recycling EVBs, however, may not be very straightforward and involves several steps, including collection, diagnosing, discharging, disassembly, sorting, and material recovery (Bhar et al., 2023). Several methods are employed to recycle EVBs, each targeting the recovery of valuable materials such as lithium, cobalt, nickel, and other metals while minimizing waste. The literature is abundant regarding the discussion on the methods for recycling EVBs and their implications (Yun et al., 2018; Makuza et al., 2021; Pinegar & Smith, 2019; Larouche et al., 2020; Gaines & Wang, 2021; Li et al., 2023b), it is possible to highlight the primary methods for recycling EVBs as being:

- Mechanical Processing: involves shredding or crushing spent EVBs to separate different components such as metal casings, plastics, and electronic components. This initial step breaks down the battery into smaller pieces, facilitating further separation of materials.
- Pyrometallurgical Recycling: employing high-temperature processes to extract metals from EVBs. Thermal treatment techniques such as smelting or roasting are utilized to separate metals from non-metallic components. This method is particularly effective for recovering valuable metals like cobalt, nickel, and copper from battery electrodes.
- Hydrometallurgical Recycling: involves leaching battery materials in a liquid solution to dissolve metals and separate them from other components. Acid leaching, solvent extraction, and precipitation processes are commonly used to recover metals like lithium, cobalt, and nickel from EVBs electrodes.
- Direct Recycling: aims to reuse battery materials without extensive processing. This approach involves refurbishing or reconditioning spent battery modules to extend their lifespan or integrating them into new battery packs with minimal material extraction. Direct recycling reduces energy consumption and environmental impact compared to traditional recycling methods.
- Electrochemical Recycling: utilizes electrochemical processes to recover metals from EVBs. Techniques such as electrodeposition and electrodialysis enable selective deposition of metals onto electrodes, facilitating their extraction from battery electrodes. Electrochemical recycling offers high purity and efficiency in metal recovery while minimizing waste generation.

These methods can be combined or adapted based on battery chemistry, composition, and desired material recovery rates (Pinegar & Smith, 2019). It is also possible to conclude that advances in recycling technologies continue to improve efficiency, reduce costs, and increase the sustainability of EVB recycling processes.

3.4 Battery Return Center capabilities

Although the focus of this study, little research is found on the specific processes for the reverse logistics of EVBs after the end of their first life and prior to the beginning of their second life applications. Nevertheless, it is possible to determine from a supply chain perspective that there are several steps to ensure an efficient return flow, such as collection, evaluation and sorting, testing, cleaning, dismantling, charging and discharging, recycling, remanufacturing and repurposing, storing, and, lastly, shipping (Prevolnik & Ziemba, 2019; Tadaros et al., 2022; Lin et al., 2023). Some of these steps may not happen inside a BRC, but still, they will be directly connected to its flow of capabilities and will be described in this chapter.

The first step of this chain of events is the *Collection* of the used EVBs from dealerships, Original Equipment Manufacturers (OEMs), designated service providers or even primary customers, done directly or by establishing collection points with programs for EV owners to return their used batteries (Meegoda et al., 2022). Once collected, batteries are transported to processing facilities using specialized handling procedures to ensure safety and compliance with local regulations. However, the work done by Slattery et al. (2021) highlights that there are many challenges and opportunities in this process, such as safety concerns due to the fact that LIBs are classified as hazardous materials given their flammability and potential for thermal runaway; cost considerations for optimizing transportation routes, minimizing travel distances, and maximizing truckload efficiency; infrastructure limitations due to insufficient collection points, recycling facilities, or transportation networks; and supply chain coordination, once the various stakeholders involved will increase the complexity of the decision making.

Upon arrival at the processing facility, batteries should undergo thorough *Inspection* and *Testing* to assess their condition and suitability for reuse. Furthermore, not all used batteries are created equal and to maximize their potential in their second life, so sorting them based on various factors is essential. Diagnostic tools and techniques are employed to evaluate factors such as capacity, voltage, internal resistance, and physical integrity (Muhammad et al., 2019b). The testing of the battery plays an indispensable role in ensuring the safe, efficient, and sustainable utilization of EVBs in their second life. By employing a combination of established and evolving testing techniques, the second-life battery market can unlock the full potential of these valuable resources, contributing to a more circular and environmentally responsible future (Zhu et al., 2021). According to Nováková et al. (2023), these tests range in complexity and required equipment, especially because the type of load during the battery’s first life significantly affects LIB aging and lifespan. Still according to the authors, the main challenges in this process arise in grouping batteries with similar state of health (SOH) and history since, currently, there's a lack of experimentally measured data spanning an EV's entire lifetime, hindering pairing with capacities at the second life's start.

Cleaning the EVBs for its second life application may be seen as a very insignificant step to be considered, however, it is an essential process to ensure optimal performance and longevity

(Chirumalla et al., 2023). The specific cleaning methods for EVBs vary depending on the battery chemistry, condition, and intended second life application. The cleaning of a battery that is being repurposed may not require opening the cell packs, which means that the batteries will be submitted to a superficial cleaning procedure of its external shell, while batteries destined to remanufacture or recycling will require specialized expertise and appropriate facilities for dealing with the more sensitive internal components (Chirumalla et al., 2023; Ramoni & Zhang, 2013).

The *Dismantling* step will only happen for the batteries destined to recycling, but it is a crucial step in ensuring environmental protection and resource recovery (Li et al., 2023a). This process involves carefully disassembling EVBs to separate various components such as the battery cells, modules, and casing. By dismantling EVBs, recyclers can efficiently recover valuable materials like lithium, cobalt, and nickel while ensuring the safe handling of hazardous substances (McDougall, 2023). However, the most common practice for disassembling the batteries is a manual process, which leads to many problems, such as low efficiency and security issues for operators, due to the nature of hazardous components inside the battery pack (Rajaeifar et al., 2022). To address the challenges in dismantling efficiency, Zhou et al. (2021) proposes a solution based on intelligent robotics that can enable a safe and efficient disassembly, while improving residual energy detection and enabling a secondary utilization of battery packs. This approach aligns with the need to systematically process and recycle lithium from EVBs as much as possible, to prevent resource wastage and close the sustainability cycle (Zhou et al., 2021).

Efficient *Charging and Discharging* strategies are another step that is essential to ensure the optimal performance of these second life EVBs. Moreover, this step will be important for two aspects of the battery second life. First, according to Haram et al. (2023) some of the testing that will address the SOH of the battery cells require a complete cycle of charging and discharging. This means that second life requirements may be measured during this and they will point the necessity for some system update or individual cell repair, and for the process of “balancing”, which means to ensure that each cell within the battery pack receives an equal charge, helping prevent overcharging of individual cells, which can lead to degradation and reduced lifespan (Haram et al., 2023). Secondly, it is expected that these batteries may be stored for a while before proceeding to their next step in the chain. Although there is no single "optimum" charge level for storing used EVBS in a warehouse, some sources indicate that charging or discharging the batteries until a range around 30-50% SOC will be able to preserve its efficiency for a longer time (Battery University, 2021).

Remanufacturing and Repurposing are the “transformation” steps that will give the used EVBs the ability to perform in their second life applications. On the refurbishing side, the process is composed of activities that have the objective of restoring used batteries to optimal performance levels through processes such as cell balancing, module reconfiguration, and component replacement (Canals Casals et al., 2017). On the other hand, functional batteries may be repurposed for second-life applications such as stationary energy storage, grid stabilization, or backup power systems and will ideally do not require opening the battery pack but, instead, be packed together and connected in such a way to create a bulky station that will be able to store and distribute energy (Thakur et al., 2022; Song et al., 2022).

Recycling EVBs involve several key steps to ensure the efficient recovery of valuable materials while minimizing environmental impact. These steps may vary from one specific recycling method to another, but on a general level, the batteries undergo disassembly, where they are dismantled into individual modules and cells. These components are then processed through various techniques such as shredding, crushing, and chemical treatments to extract the valuable materials (Chen et al., 2019). Subsequently, these resources are purified and refined for reuse in battery production or other industrial applications (Chen et al., 2019; Zhang et al., 2023). Lastly, it is important to build up a flow to perform a proper disposal of hazardous by-products and environmentally responsible practices are integral throughout the recycling process to mitigate potential ecological harm (Zhang et al. 2023; Tao et al., 2021).

As previously described, it can be expected that the batteries in a process for their second life preparation will spend some time under *Storage*. LIBs, however, are sensitive and dangerous materials that require a number of regulations and best practices in place to assure safety for the environment and people in contact with these materials in a day-to-day operation (Chen et al., 2021). For example, the new European Law on batteries describe the storage and treatment, including recycling, requirements as:

"1. *Treatment shall, as a minimum, include removal of all fluids and acids.*

2. Treatment and any storage, including temporary storage, at treatment facilities, including recycling facilities, shall take place in sites with impermeable surfaces and suitable weatherproof covering or in suitable containers.

3. Waste batteries in treatment facilities, including recycling facilities, shall be stored in such a way that they are not mixed with waste from conductive or combustible materials.

4. Special precautions and safety measures shall be in place for the treatment of waste lithium-based batteries during handling, sorting and storage. Such measures shall include protection from exposure to:

(a) excessive heat, such as high temperatures, fire or direct sunlight;

(b) water, such as precipitation and flooding;

(c) any crushing or physical damage.

Waste lithium-based batteries shall be stored in their normally installed orientation, that is, never inverted, and in well-ventilated areas and they shall be covered with a high voltage rubber isolation. Storage facilities for waste lithium-based batteries shall be marked with a warning sign." (European Union, 2023. ANNEX XII, Part A). By implementing these practices, you can ensure the safe, efficient, and responsible storage of used EVBs, extending their lifespan and maximizing their potential for valuable second life applications.

The last capability to be explored is the *Shipping* and, in theory, this process will share much of the transportation done in the collection phase, but here there is an increased complexity in terms of documentation (as the shipment can be of used batteries, waste batteries, remanufactured batteries, ESS, etc.), logistical challenges (with different sizes, weights, compositions and products), and personnel training (Slaterry et al., 2021). Regarding regulations, the new European Law on batteries (European Union, 2023. ANNEX XIV) also presents a description of all requirements that companies should take into consideration before shipping batteries in order to guarantee that all legal standards are being met.

Overall, the return process of EVBs for their second life involves comprehensive planning, coordination, and execution to realize the full potential of these batteries beyond their initial use in EVs. By adopting sustainable practices and embracing CE principles, stakeholders can optimize value creation and contribute to a more resilient and environmentally conscious energy ecosystem.

3.5 Challenges for Battery Return Center implementation and scalability

Quite a few challenges influencing the extensive acceptance of second life EVBs and the implementation of the return flow of the necessary reverse logistics have been identified by researchers such as Shahjalal et al. (2022) and Ferrara et al. (2021), who provide an overview of strategic, organizational and economic barriers. Martinez-Laserna et al. (2018) and Gu et al. (2024), on the other hand, examine the challenges as characteristics of technical aspects, technological viability and regulatory barriers, as well as safety and responsibility issues. Table 3.2 summarizes the primary obstacles outlined in the literature, covering technical, economic, internal, organizational, and regulatory aspects that hinder the expansion of second life projects.

Table 3.2 - Barriers to BRC implementation and scalability.

Sources: Shahjalal et al. (2022); Ferrara et al. (2021); Martinez-Laserna et al. (2018); Gu et al. (2024); Muhammad et al. (2019a); Canals Casals et al. (2017); Vu et al. (2020); Beaudet et al. (2020)

Barriers to BRC implementation and scalability	
Technical	Logistics and transportation
	Battery degradation and sorting
	Battery state assessment
	Lack of knowledge
Economic	High cost of Recycling / Remanufacturing / Repurposing
	High investment
	Current economy of scale
Internal / Organizational	Lack of standardization
	Lack of infrastructure
	Safety concerns
Regulatory	Regulatory and policy frameworks
	Future recovery targets

EVBs are heavy and bulky, which makes their transportation back to BRC facilities challenging and costly, and establishing efficient logistics networks for collecting and transporting used batteries is essential but can be complex and expensive (Vu et al., 2020). After their first life, EVBs may have varying levels of degradation and performance, and sorting batteries based on their SOH and capacity is necessary to determine their suitability for second-life applications or recycling (Martinez-Laserna et al., 2018). Hence, developing efficient sorting technologies that can accurately assess the condition of used batteries is essential (Gu et al., 2024). Likewise, accurately gauging the remaining capacity and health of each used battery is crucial for deciding its best course of action (remanufacture, repurpose, or recycling), but this can be a complex process, requiring advanced diagnostic tools, techniques and specialized personnel (Muhammad et al., 2019a).

Unlike traditional lead-acid batteries, LIBs pose unique challenges due to their complex chemistry and composition and many stakeholders, including manufacturers, recyclers, policymakers, and consumers, lack sufficient knowledge about the most effective methods for extracting valuable materials from these batteries while minimizing environmental impact (Ferrara et al., 2021). Another aspect contributing to the lack of knowledge is the relatively short history of widespread EV adoption. With EVs still being a relatively new technology compared to conventional vehicles, there is a lack of long-term data and research on the behavior of EVBs over extended periods (Gu et al., 2024). This limited understanding hampers efforts to develop efficient and sustainable end-of-life management strategies.

Recycling EVBs involves complex processes to extract valuable materials while minimizing environmental impact. However, the cost of recycling these batteries can be high, particularly when compared to the value and amount of the recovered materials, that is why finding economically viable recycling methods is crucial to incentivize the returning flow of EVBs (Shahjalal et al., 2022). It is similarly expensive to perform the activities necessary for the other second life alternatives (remanufacture and repurpose) and Shahjalal et al. (2022) also performs a cost analysis to evaluate these alternatives implementation.

Another economic aspect that can be considered is the high level of investment necessary for creating efficient operations, this refers to resources for space, equipment, and processes implementation, but also include increasing funding for repurposing and recycling technology innovation, supporting pilot projects, and even implementing market-pull measures to create a favorable economic and regulatory environment for large-scale EVB reutilization and recycling (Beaudet et al., 2020). It is also possible to highlight that to be cost-effective, the transformation process for second life EVBs is dependent on high returning quantities due to high fixed costs (Canals Casals et al., 2017). However, large numbers of LIBs in their end of first life are not expected before 2030 (Tankou et al., 2023).

Different EV manufacturers use batteries with varying designs, chemistries, and materials. This lack of standardization makes it challenging to develop efficient and cost-effective recycling or repurposing methods applicable to a wide range of batteries (Gu et al. 2024). Additionally, there is little consensus on how companies involved in the reverse logistics flow should operate, which increases the complexity of managing service suppliers (Slattery, 2021).

As the adoption of EVs continues to grow, the volume of used EVBs into the return flow for their second life preparation will increase significantly. Scaling up infrastructure and capacity to handle this volume is crucial to prevent bottlenecks and ensure timely and efficient battery recycling (Shahjalal et al., 2022). Likewise, much of the work that is done nowadays is manual and labor intensive, then, infrastructure should also improve in terms of automation in order to achieve reasonable levels of scalability (Shahjalal et al., 2022).

Organizations should also consider barriers regarding safety concerns, once used EVBs still contain potentially hazardous materials for the environment and people involved in the handling of the processes (Shahjalal et al., 2022). Similarly, residual energy stored in the batteries may present a threat of temperature spikes leading to fires and explosions (Ferrara et al., 2021). Therefore, ensuring the safe handling and transportation of these batteries to recycling facilities is critical to prevent possible accidents and environmental damage.

Establishing regulatory frameworks and policies to incentivize the return and recycling of EVBs is essential. Governments may need to implement measures such as extended producer responsibility (EPR) schemes or financial incentives for battery recycling to encourage compliance from manufacturers and consumers and to achieve electricity market advancements, and stricter battery safety protocols that will raise the potential economic advantages from extensive large-scale second-life batteries deployment. (Ferrara et al., 2021; Gu et al., 2024). Lastly, regulations such as the new Battery Law in place in the European Union are setting restrictions for managing used batteries or targets for recycling recovery efficiency (European Union, 2023), which may lead companies to face a much bigger entrance blockage that should be overcome only to enter the business segment.

4 Empirics

This chapter aims to describe and analyze the collected data. Firstly, section 4.1 will provide an exploration of the concepts introduced in the literature review. Secondly, the companies that participated in the interview process will be introduced in section 4.2, following by the interpretation of the data gathered from the interviews, and how all explored concepts mix for influencing a BRC framework.

4.1 Model capabilities for a BRC from a supply chain perspective

The decisions concerning the reverse flow and the EOL solutions for EVBs after their first life are complex and require a focus on shifting from a straightforward supply chain towards a closed-loop perspective (Prevolnik & Ziemba, 2019). The implementation of the closed-loop system brings forth many challenges regarding the logistical process that companies in this area must face, like the macro procedures for moving, treating, and storing EVBs (Sharmili et al., 2023). However, the knowledge and the regulatory framework surrounding the preparations of EVBs for second-life applications at their EOL phase are still not clear for the organizations that operate in this field (Sharmili et al., 2023). In the next subsections, analysis from existing academic works and the current EU regulation for dealing with EOL batteries are presented and combined to, firstly, demonstrate the capabilities that will be composed of more general tasks and that will be applied to all batteries in the flow, named ‘Basic Capabilities’. Then, the more complex and technical activities will be presented under the name of ‘Advanced Capabilities’. The steps for creating a second life product, e.g., opening the battery for repair, recycling internal components, or the final assembly of an Energy Storage Systems (ESS) with repurposed EVBs are considered outside the reach of a BRC, hence will not be explored. Lastly, a summary of the complete capabilities’ scenario that a BRC should have will be presented in detail.

4.1.1 Basic Capabilities

Some of the activities in the reverse logistics flow are common to all EVBs in preparation for their second life, regardless of their end purpose being remanufacturing, repurposing, or recycling. Additionally, the level of complexity of the activities may also vary from each other: From steps that take minutes from others that require hours of operation.

The internal process in the BRC will start at the *Receiving* of the batteries. The receiving of the EVBs is intrinsically connected to the outside collection from the dealers, OEMs or consumers, and an efficient flow will require some actions to be taken for guaranteeing that the batteries are in the correct package, carrying an adequate label, and having the information related to their SOH. Shahjalal et al. (2022) conducted a review on the prospects, challenges, and issues for the second life of EVBs and their finding indicate that the lack of standardization on the collection of the batteries is one of the main blockers for the second life process. This can be seen, for example, in the fact that if the information on the batteries on their arrival is not precise, the receiving operation can have a problem identifying the origin and internal destination that each EVB should follow. On the regulatory side, two main aspects based on EU Regulation play a particularly strong role, labeling and information traceability. For the first, the regulation states that there is minimum amount of information that must be printed on a label that is attached to the battery in transportation and a QR code that can be read to provide access to the battery’s passport where all historical information should be available (European Union, 2023, Annex VI). Secondly, the regulation also writes that the BMS must carry up-to-date information at any moment that it may be accessed in the flow, and that “*the battery management system shall include a software reset function, in case economic operators carrying out preparation for re-use, preparation for repurposing, repurposing or remanufacturing need to upload different battery management system software*” (European Union, 2023, p. 38). The reset function is crucial for updates, but also to address the correct ownership and liability (in terms of security and functionality) after the EVB was placed on the market once again.

The next capability in the flow is to perform an external *Inspection* on battery to evaluate the overall condition of the packing, if there is no visible damage that would require special attention (e.g., leaking), and if the regulatory information is in place. Additionally, contingency actions should be prepared beforehand to deal with possible anomalies.

Then, the EVBs in the BRC shall follow a *Sorting* process. Which will act as a preliminary decision step based on all the information available at this point, especially the historical data and the original intent of the battery in being returned. This activity in the process can send the batteries either to the ‘Advanced Capabilities’ flow or directly to the shipping step, in case they are identified as EVBs for re-use, repair or refurbishment, which will send them back to the first life channel; or for recycling.

At the very end of the flow, the *Shipping* capability is going to be responsible for the internal warehousing process of picking in the EVBs from stock and shipping them to customers or partners. This process can also be integrated to the already existing logistical setup companies currently have, as long as the special requirements for transporting used batteries are followed as described in the current EU Regulation (European Union, 2023, Annex XIV), this means that adaptations can be made, but still there is no need to create a unique flow only for these activities. Hence, many 3PL companies, such as DHL for example, are adapting their own existing operations to offer transportation and storage solutions to used EVBs (DHL, 2024).

4.1.2 Advanced Capabilities

The first capability in the advanced flow is the *Pre-Diagnosis* of the EVBs. This step is responsible for performing a screening on the EVBs for potential second-life use and determining if they, in fact, have the minimum requirements of SOH for that. As described before, the batteries enter the return flow carrying some level of information that indicates a second life use, however, it is necessary to increase the confidence on the information that each EVB is correctly addressed to the better use it could have. Which is important for assuring that adding-value activities in this flow are not being performed in batteries not fit enough for a second life application. For example, batteries that will be recycled should not spend time in a charging station.

Following that, the *Cleaning* capability will be in place aiming to achieve two main purposes. First, as described by Chirumalla et al. (2023), by externally cleaning the pack of the batteries, it is possible to make sure that the operators in the processes can safely interact with the battery pack, but also directly facilitating the following steps that an EVB undergo in the return flow. This is crucial to ensure optimal performance and longevity for the second life product.

Secondly, by cleaning the battery pack it will become much more visually pleasant, hence adding value to the final product that will later be sold to customers.

If the battery was classified as an item for recycling after the pre-diagnosis step, it should be directed to a *Dismantling* step to have their internal components separated for the different recycling processes that will be performed. For instance, there are many plastic and metal parts that will be destined for a usual recycling process, but the sensitive valuable minerals (e.g., lithium and platinum) will have their own specific recycling methods applied. The dismantling will be marked as a possible block in the process, but it may also very well not be included. As previously described, the steps for creating a second life product will not be part of the framework of capabilities included in this work, and the dismantling of the battery pack is usually a step inside the recycling process. However, if a BRC have a recycling company or organization internally linked to its processes, which means that the subproducts of the dismantle will not have to be shipped outside of the premises, it would make sense to have the dismantle step at the beginning of the advanced capabilities flow.

The next two capabilities, *Charging / Discharging* and *Testing*, will be placed together as they are intrinsically connected and may even be performed at the same time. To charge or discharge the battery is necessary to place the charge level within the range between 30 and 50%, which manufacturers indicate to be ideal one to keep EVBs stored (Battery University, 2021). The charge level is important for protecting the circuit of disconnected devices by preventing thermal runaway and degradation of battery cells (Zhao et al. 2021). Additionally, it is during this step that the balancing of the cell modules is going to be performed, and this is crucial for getting more accurate data in the tests that are going to be done for creating a report on battery's SOH and capacity. There are many ways of executing the *Testing* capability, with different techniques, technologies, and equipment. But there is a minimum amount of information that has to be extracted from the testing process for it to be in line to what is described in the current EU Regulation specifications, namely state of certified energy (SOCE), the remaining capacity, the remaining power capability, the remaining round-trip efficiency, the evolution of self-discharging rates, and the ohmic resistance. (European Union, 2023, Annex VII). Lastly, reinforcing the idea that a BRC should not be a place to directly deal with internal components of EVBs, Hantanasirisakul & Sawangphruk (2023) describe that the battery modules are preferably tested without disassembling, mostly because of the high cost and safety hazard of disassembling and reassembling processes.

Afterwards, the EVBs in the flow will go through the *Storing* process until the point they are ready to be shipped. This step is classified as an advanced capability due to the very specific requirements that EVBs impose for being kept stored. On one side, there is a performance aspect, where EVBs are susceptible to an aging process that leads to reduction of the batteries' lifespan. For example, Zhang et al. (2021a) developed a study to explore the influence of room temperature in EVBs storage places, reaching the conclusion that EVBs stored at higher temperature (above 60 °C) have an accelerated rate of aging at room temperature and may even become unfit for second life applications after 15 days in this environment. Although it is not expected that a normal warehouse will reach this temperature level by its own, it is important to note that the energy charge level that batteries hold can trigger temperature spikes and expose internal components to this temperature range (Zhang et al., 2021a). The second aspect is related to the safety of the stock area and the personnel responsible for interacting with the stored EVBs. For that, EU regulation highlights that the battery packages should act as electric isolation, be able to hold leaking, and be impermeable, while all the storage space (even temporary ones) have to be exclusive for the batteries and include protection to excessive heat, such as high temperatures, fire or direct sunlight; water, such as precipitation and flooding; and any crushing or physical damage (European Union, 2023, Annex XII).

4.1.3 Capabilities Summary

For creating a better visualization on topics discussed in sections 4.1.1 and 4.1.2, Tables 4.1 and 4.2 summarize the main details extracted from academic works and also points on the regulatory source that is connected to each capability.

Table 4.1 - Basic Capabilities summary

Level	Capabilities	Academic inputs	Regulation (EU) 2023 /1542
Basic	Receiving	Authors highlight the need for increased standardization in the inbound logistics processes and a better integration to 3PLs	Annex XIV: Minimum requirements for shipments of used batteries.
	Inspection	Some works emphasize the use of testing techniques that can be performed at this point in the flow, but they can become duplicated to the other testing that EVBs are intended to perform.	Annex VI: Labelling, marking and information requirements
	Sorting	One of the biggest intakes for this step in the opportunity to incorporate automation for increased performance	No details
	Shipping	Many works highlight transportation as an economic challenge due to the limited volume, different regulations for different countries and still few players in the market. "LIBs must be removed from the vehicle, potentially stored until enough batteries accumulate for a cost-effective shipment, and be transported to the appropriate facility" (Slattery et al., 2021)	Annex XIV: Minimum requirements for shipments of used batteries. & Annex VI: Labelling, marking and information requirements

Table 4.2 - Advanced Capabilities summary

Level	Capabilities	Academic Input	Regulation (EU) 2023 /1542
Advanced	Pre-Diagnosis	Scarce information. The creation of this capability is being proposed by the author	No details
	Cleaning	Information is present only in research of recycling methods, which requires the dismantling of battery packs for internal cleaning	No details
	Dismantling (optional)	Intrinsically connected to the recycling process. Authors highlight the necessity of increasing standardization of battery models to improve efficiency	Main body & Annex XIII: Information to be included in the battery passport
	Charging / Discharging	Many works mention a 20% minimum SOC, but there is no consensus on a "correct" value	No details
	Testing	Researchers are focusing of 2 points: 1. Continual estimation of battery health (historical data from battery reading during operation in the first life) 2. In-depth testing of the battery cells using proper equipment and technology	Annex VII: Parameters for determining the state of health and expected lifetime of batteries
	Storing	1. Strong focus on local regulations 2. Some highlighted that storage of LIBs also needs to consider the possibility of batteries changing from non-critical to critical and safety measures for such events needing to be taken in advance.	Annex XII: Storage and treatment, including recycling, requirements
	Second life preparation	Scarce information. The creation of this capability is being proposed by the author	Annex XII: Storage and treatment, including recycling, requirements. & Annex XIII: Information to be included in the battery passport

4.2 Best practices for the Reverse Logistics of EVBs at the end of their first life

This section presents results for *RQ2* by first providing an industry overview of the business for EVBs second life solutions (which). Then, their best practices are presented to understand the supply and operationalization flow (how). Lastly, exploring the external and internal influencing factors on our Conceptual Framework (why).

4.2.1 Industry overview

As described in the methodology chapter, both companies that are exclusively inside the automotive industry and others that have a broader reach were investigated for creating an understanding of the capabilities needed on a BRC flow. Table 4.3 offers a summary of these companies' segments and the main service provided related to EVBs. This information was gathered from companies' websites as well as from the interviews conducted with each of them. The companies that participated in the interview process were selected either by direct contact from the author or through internal connection from Volvo Group, prioritizing organizations that had a direct relation to the automotive sector in the initial phase and then exploring possible cases in all industry fields.

The findings indicate that most organizations do not publicly disclose details in their activities for preparing EVBs for second life or even on how the solutions that are sold are created. This lack of transparency suggests a potential protectionism to their processes and, given that this business area is still filled with uncertainty, companies may either try to block the entrance of new competitors or try to create unique solutions to potential customers. However, interviews revealed that all the companies are engaged in Research and Development of techniques, processes, products, and services that may become a future standard for the industry. Many of these projects are in the pilot phase, aimed at assessing the technical and economic viability of such efforts and preparing for an anticipated increase in the volume of returned EVBs in the future.

Table 4.3 - Interviewed companies' overview

					EVBs 2nd life strategy			
#	**Company**	**Country**	**Segment**	**Service provided**	**Repair**	**Remanufacturing**	**Repurposing**	**Recycling**
1	Company A	U.S.A.	Automotive	Battery lifecycle management	x	x	x	x
2	Company B	Germany	General (all batteries)	Second Life Battery Solutions		x	x	x
3	Company C	India	General (all batteries)	Second Life Battery Solutions			x	x
4	Company D	Finland	Energy	Second Life Battery Solutions			x	x
5	Company E	Brazil	Automotive	Battery lifecycle management	x	x	x	
6	Company F	Spain	Urban mobility	Battery recovery	x			x

Some of the companies interviewed may focus only on some strategies for dealing with second life EVBs, with repurposing and recycling being the most prominent among the participants. In contrast to all other participants, Company E reportedly as not having a recycling process in place, yet it was later explained in the interview that they have another company inside their organization focusing only on the recycling of LIBs and lead-acid batteries (used in internal combustion engine vehicles). Surprisingly, repair and remanufacturing appeared to be the least explored strategies, in contrast to the concepts previously discussed in chapter 3 for CE strategies. In that sense, Company D pointed out that repairing and remanufacturing of EVBs tends to be done internally by the vehicle manufacturing companies or by their EVB providers, due to the particularity of each model and the warranty processes. Lastly, all companies indicated that they have plans for expanding their business for providing services on all CE strategies, as the market practices become more mature and the volume of EVBs for second life applications scale to a point that justifies the increased investment.

Although the participant companies are from different continents, namely America, Europe, and Asia, all of them informed having business within the European Union and being aware of the regulation in place for this region. Company C, for example, stated that the new EU battery regulation from 2023 have many points in common to the current Indian regulation, that is older, which is giving them a competitive advantage for running their operations inside Europe. Additionally, the services that each company is providing to their customers may change slightly from each other. For example, Company A explained that their objective is to be a complete service provider, where both companies or end users may reach them for a solution related to LIBs, which could range from simply buying a repaired EVB to building up a complete network for collecting batteries from a given manufacturer and transforming them into ESS products. On the other hand, Company F built a facility specialized in repairing only smaller versions of EVBs (i.e., e-bikes, scooters, small cars) and recycling batteries beyond repair.

4.2.2 Operationalization of the Return Logistics and EVB second life flow

The operationalization of the logistical flow is a critical aspect for understanding how EVBs transition from their first into their second life. The companies involved in this study emphasize the impact of expertise for their operation, while providing value-added services within the framework of a value chain. Their motivation lies in building a supply chain network capable of efficiently managing the growing influx of returned EVBs.

Tables 4.4 and 4.5 summarize the core ideas acquired from the interviews using the guide in Appendix B, categorized into the same topics. For a better visualization, the general concepts involving the explored concepts were placed on Table 4.4, while the processes related to the BRC capabilities were placed on Table 4.5.

Table 4.4 - Core ideas for general concepts

Topic	Core ideas
Lifecycle and Strategy	Having innovation and sustainability as core values
	Maximize batteries' lifecycle
	To offer complete solutions for the second life of EVBs
	Creating innovative products for a new and fertile market
	Finding solutions to problems related to the second life of EV batteries
Return Cycle	Each company is trying to create its own flow of returning batteries from OEM, dealers, or consumers
	Purchasing is done based on suppliers' information and batteries are tested after arriving to validate physical condition and SOH
	Labeling and packaging are done following local regulations or UN Dangerous Goods guidelines for packaging
	Some companies have an 'open' purchasing process (accepts EVBs from individuals and other companies) and others have a 'closed supply chain' (only receiving batteries from fixed contracts and partnerships)
	There is a strong preference for non-critical batteries, but almost all companies have processes in place to deal with both critical and non-critical EVBs
Future Perspectives	Increased efficiency of material recovery in the recycling processes
	The business area has a strong confidence to scale up in an almost exponential rate
	To create a better understanding of regulations and how to deal with different rules among countries
	To create standardized processes across the whole supply chain

Lifecycle and Strategy

To set the initial scenario, the interviews tried to explore how each participant company deals with EVBs lifecycle and what is the strategies that they are applying to nurture the CE in their businesses. All companies described a tight relation to innovation principles and sustainability, which, according to Company A, is of utmost need that these two aspects represent the core values of their organization. They explain that in a very uncertain and naive market, innovation plays the role of setting the future standards for the business, and companies that reach this point first have a clear advantage. Additionally, Company B underlined that sustainability can be seen as a new way of doing business, where profit can be aligned to creating a better environment for everyone to prosper, not only a single company but also customers, community, and even competition.

All the companies also emphasized the maximization of EVBs lifecycle as an important point in their strategies, although they might differ on their internal proposition on how to accomplish this achievement. Company C, for example, aim to become a flagship on Indian market by proposing innovative solutions to extend the operational life of EVBs to their maximum, which they intend to achieve by creating big partnerships with manufacturers and OEMs that can joint on the development of new technologies. Likewise, company D reportedly having many layers of investment (internal and external) for increasing the efficiency of material recovery on their recycling processes. Alternatively, Companies A and B are spreading their investments with the objective of creating a complete solution option for a more diverse range of customers. Their goal seems to aim on becoming a "central collection and selling point" where all the reverse logistics could be centralized, and for being recognized as a reference in the industry by raising the standards of a company that offers complete solutions for second life of EVBs.

Some companies are also trying to fill a niche of the market, which is the case for Company E, a big LIBs manufacturer that is investing in their internal market to develop customized solutions for the Brazilian OEMs and car manufacturers, considering all their particularities. Which can be seen as a challenge, but also a fruitful opportunity, because this is one of the focus countries for the big EV manufacturers, according to Company E, but that still lacks greatly on infrastructure, hindering the market share for EV on road transportation.

Although the sales of EVs are steadily increasing each year, suggesting a significant business opportunity in managing EVBs at their EOL, the young age of the market makes that not many EVBs can be found in the EOL point, which classify the volume as a challenge for the companies involved. Company F stated that this scenario creates uncertainty and poses challenges in developing viable business models, as they heavily rely on predictions. They also mentioned that the uncertainty has a direct impact in the operational costs and that creative solutions for common logistical problems, i.e., truckload, capacity, or time schedules, are many times needed, but, most importantly, strengthen the ability to deal with different possible scenarios.

Return Cycle

The young age of EVBs second life market creates a scenario where the flow of the reverse logistics is also open to many different interpretations and strategies. All companies reported as trying to tailor their operations to address their internal challenges and on trying to extract the best possible relation between cost and benefit. Company B, for instance, is creating an online platform where suppliers can pre-negotiate the EVBs they have in possession, by filling in information such as model, year, and SOH. This will give then a price estimate that should be confirmed after the EVB arrives at the facility and undergo a simple check to verify the provided information and to see if the battery is in good physical condition. Other companies, such as Company D, are focusing on strengthening the relationship between all players in the supply chain. Each time a new company joins the chain for a partnership, a whole set of parameters are put into place to optimize the collection, transportation and regulatory steps that are required prior to the arrival of the EVB for the second life operationalization. Although different strategies are being followed by the companies, there is no way to measure which of them can provide better efficiency, profit margins or even customer satisfaction, because the number of unknown variables is still too big.

Ensuring the safe transportation of EVBs is paramount due to their potential risks of them being mishandled and injuring people or the environment. Local regulations vary across different regions and countries, dictating specific requirements for labeling and packaging to mitigate potential hazards associated with EVBs. Company F highlight that these regulations in the EU comprehend aspects such as specific labels to be placed in the battery and information that should be readable without opening the pack; packaging materials to isolate the battery from external humidity, light, and electromagnetic fields; and, lastly, transportation methods to safeguard both the environment and human health. Alternatively, EVBs may be packaged and labeled in accordance with the UN Dangerous Goods guidelines. Company C, that follow them, cited that these internationally recognized guidelines provide a standardized framework for the classification, packaging, marking, and labeling of hazardous materials, including LIBs; and for an organization that have operations on multiple countries and continents these guidelines can be preferable for having an ample acceptance by multiple governments. By adhering to these guidelines, EVB manufacturers, distributors, and logistics providers ensure compliance with global standards, facilitating the safe and efficient transportation of EVBs across borders. It is important to highlight that, in either case, meticulous attention should be paid to properly labelling EVBs with pertinent information such as battery type, voltage, capacity, and any associated hazards. Additionally, EVBs are packaged using suitable materials designed to withstand transportation conditions and prevent damage or leakage during transit.

For sourcing EVBs at the end of their first life, the interviewed companies employ either an approach that can be considered an 'open' purchasing process or opting for a 'closed supply chain' model. In an 'open' purchasing process, companies welcome EVBs from a diverse range of sources, including individuals and other companies. Company A states that this inclusive approach allows for a broad spectrum of batteries to be considered for second life applications. By accepting EVBs from various sources, they can potentially access a larger pool of batteries, thereby increasing their supply and diversity of available resources. Additionally, this approach fosters collaboration and engagement with individuals and other businesses, promoting a sense of community and environmental responsibility. On the other hand, a 'closed supply chain' model involves companies exclusively sourcing EVBs through fixed contracts and partnerships with specific suppliers. During the interview, Company E said that this may be a more restrictive approach, but it prioritizes reliability, consistency, and quality control in the procurement process. Especially for a company like themselves, that has a direct supply to automotive manufacturers, establishing fixed contracts and partnerships can ensure a steady and reliable supply of EVBs that meet their predetermined standards and specifications. Furthermore, this model allows for closer collaboration and alignment between suppliers and purchasers, facilitating streamlined communication and coordination throughout the supply chain. Both approaches have their merits and considerations. The 'open' purchasing process offers flexibility, diversity, and community engagement, while the 'closed supply chain' model prioritizes reliability, consistency, and quality control. Ultimately, the choice between these approaches depends on factors such as business objectives, risk tolerance, resource availability, and the desired level of control over the supply chain.

Another aspect observed in relation to the return flow of EVBs was that most companies exhibit a strong preference for non-critical batteries, yet most remain equipped to handle both critical and non-critical EVBs. Non-critical batteries refer to those with diminished capacity or performance that no longer meet the demanding requirements of EVs but still retain usability for less demanding applications (Neumann et al., 2022). Company B highlighted that these EVBs may still hold a significant amount of energy and lifespan suitable for secondary use cases such as stationary energy storage for renewable energy systems or grid stabilization, and that the products created by them hold a much higher aggregated value than simply recycling them for material recovery. Moreover, repurposing non-critical batteries aligns with sustainability goals by extending the useful lifespan of these resources and reducing environmental impact. In contrast, critical batteries typically refer to those with severe degradation, safety concerns, or other significant issues that render them unsuitable for secondary use without extensive refurbishment or recycling (Neumann et al., 2022). Company D cited that while less common, what makes critical batteries less attractable is that they require special handling and management to mitigate safety risks and environmental impact, increasing costs and lowering the possibilities for second life applications other than recycling. However, Company D also stated that by maintaining flexibility and adaptability in their processes, they ensure they can effectively manage a diverse range of EVBs while maximizing value extraction and minimizing waste throughout the second-life battery ecosystem.

Future Perspectives

Recycling is present in almost all interviewed companies and, even for the ones where it is not their main strategy, they reported as actively exploring strategies to enhance the efficiency of material recovery, anticipating the expected increase in demand for rare metals and to expand their options for sustainable battery solutions and minimizing environmental impact. Company D emphasizes that one key approach involves investing in advanced recycling technologies. These technologies leverage innovative processes such as hydrometallurgical and pyrometallurgical techniques (presented on section 3.3) to recover valuable metals from EVBs more efficiently. By optimizing these processes, Company D can extract a higher percentage of metals like lithium, cobalt, nickel, and manganese from spent batteries, reducing the need for primary resource extraction and decreasing reliance of EVB manufacturers on virgin materials. Additionally, Company B reportedly focusing on working closely with EVB manufacturers to improve battery design for recyclability. Designing EVBs with disassembly and separation in mind can streamline the recycling process by facilitating easier access to internal components and materials, simplifying the sorting process and improving the recycling flow efficiency.

All companies participating in the research poised a strong assurance that the business area is on an upward trend that is expected to continue and expand for many years ahead. The reasons behind this confidence are the same as described in Chapter 1 and Chapter 3 of this thesis. Nevertheless, Company C stated a good overview: “*(...) there is an intersection of favorable market trends, technological advancements, and regulatory support. The second life EVB business sector is well-positioned to experience exponential growth in the future, offering promising scenarios for stakeholders and driving positive impacts on society*.”

These regulations for dealing with EVBs at the end of their first life encompass various aspects such as transportation, storage, recycling, and disposal of EVBs and their components. Most companies cited having constant efforts to create comprehensive understanding of regulations governing the handling and management of EVBs to ensure compliance, mitigate risks, and facilitate sustainable business practices. Company B highlighted that they pay special attention to this matter because regulations governing EVBs are also subject to change as technology advances, environmental concerns evolve, and policymakers enact new legislation. This reinforces that maintaining a proactive approach to monitoring regulatory developments and engaging with relevant authorities and industry stakeholders is essential for staying compliant and adapting to regulatory changes effectively. Moreover, Company F emphasizes the need to extend the compliance of the regulations to external parties, especially transportations companies, as they are a crucial component of the supply chain, and their operations encompass many regulatory aspects.

The last topic raised on future perspectives was about establishing standardized processes across the entire supply chain for second life EVBs. Most companies pointed this as a key element for minimizing errors, reducing operational inefficiencies, and optimizing resource utilization. For example, Company D expressed that they believe in creating a strong standard operation network to facilitate seamless coordination and communication among stakeholders, enhancing the overall supply chain performance. Furthermore, Company C mentioned that an increase on standardized processes by external partners would facilitate their scalability and interoperability and, as the demand for second life EVBs grows and the industry evolves, the standardized processes would also enable an efficient scale of their operation.

Table 4.5 - Core ideas for BRC capabilities

Topic	Sub-Topic	Core ideas	Additional information
Remanufacturing / Repurposing / Recycling	Sorting	Testing after arrival define battery destination: remanufacture / repurpose or recycling	Usually, companies have different physical flows for each classification
		Step also used to separate critical and non-critical batteries' processes and destination	
	Cleaning	All companies reported a simple cleaning process for repurposing of batteries	Steps include pressurized air for dust and wiping (steel and plastic parts only) for grease
		For battery reman and recycling, specific steps are required for interacting with battery modules	Steps include removal or containment of hazardous substances, such as electrolyte, solvents, and metals, to prevent environmental contamination and worker exposure
	Charging / Discharging	All companies reported a charging/discharging step to set batteries between 30 and 40% SoC or nominal voltage	This step may happen more than once during the process
		The process of balancing the battery cells happen at this step	
	Diagnosing / Testing	Some companies run complete diagnosis on all batteries in the flow	These companies have a strategy to build ESS solutions, developed own testing processes that don't take very long times, or are exploring failed batteries problems to generate information
		Others run a complete diagnosis only on a part of the batteries that goes into the process	Generally random or battery with error indicated by BMS. These companies usually have a more ample offering of final products / solutions
	Storing	Companies usually worry on keeping the battery stock in a special designated area, with no direct sunlight and mild temperature control using ventilation	
		Companies reported a range between 90- and 180-days maximum storage time, based on local regulation or internal standard	Given the current market conditions (demand > offer) and FIFO strategies, batteries are rarely stored that long
		Companies reported that there are processes in place to monitor SoC and charge battery if necessary	
	Shipping	Picking processes are usually integrated to regular WMS	
		All companies reported following local regulations for labeling and documentation (EU, USA, India, Brazil)	
		Some companies have internal transportation operations and others partnership with 3PLs	
	Challenges / Bottleneck	Although companies have internal standards, it seems to be a challenge for them to expand those for partners, regarding storage and transportation	
		High mix of battery types / manufacturers increase the complexity of creating ESS when repurposing	
		Collection of batteries and the nascent Battery Waste Management rules	
	Success Factors	One of the main success factors is to create collaboration with supply chain partners for making a closed-loop strategy	
		Activities for recycling are usually integrated to other processes, and the SOH is the defining point to the battery destination	

Remanufacturing / Repurposing / Recycling

Sorting

Before EVBs follow to their second life destination, they undergo careful sorting procedures to determine their condition and suitability for different EOL management options. At this initial step, companies usually have a series of checks and quick analysis to superficially verify the battery's condition and to evaluate if the information connected to each specific EVB is correct. At this point, Company B cites that there is a "pre-testing" process to perform an evaluation of the EVB's physical condition. This involves visual inspections to check for signs of physical damage, corrosion, or degradation. Any abnormalities such as leaks, swelling, or deformation may indicate internal issues that would need further investigation. Company C, in addition, cited that there is also a bureaucratic process connected to the sorting of the batteries that may be undervalued. For them, information such as battery age, model, manufacturer, and usage history are reviewed to better understand the EVB's lifecycle and determine potential remanufacturing or repurposing opportunities. Also, each EVB is assigned a unique identifier or barcode to track its movement throughout the next processing stages. This ensures traceability and facilitates accurate record-keeping. Moreover, it is in the sorting process that companies create a separate flow for batteries that are classified as critical and non-critical, since all the following steps will depend on this information.

Cleaning

The next operational step is a cleaning process for the EVB, given the fact that after finishing their first life and removal from the vehicle, the battery's external condition is usually carrying considerable amount of dirt and debris. According to Company A, the cleaning process begin with the removal of external contaminants and remains from the EVBs external case. This typically involves wiping down the battery casings and terminals, the company also states that the use of any chemical products for the external cleaning is not a common practice to avoid using abrasive materials that could damage the battery components, however, a mild detergent solution and clean water can be used to remove dirt, grease, and other surface impurities in special cases. Most of the time, for the majority of interviewed companies, the cleaning is purely physical and can be assisted by pressurized air in the non-sensible parts. Once the external surfaces are cleaned, technicians from Company E inspect the batteries for any signs of corrosion or oxidation buildup on the terminals and connectors, so they can be carefully removed using appropriate cleaning tools and techniques to restore proper electrical conductivity and ensure reliable performance.

After the external cleaning is complete, batteries that are destined for repurposing follow the process flow to the next steps. However, EVBs that are planned to be repaired, remanufactured, or recycled, may undergo internal cleaning procedures to remove any accumulated dust, debris, or electrolyte residue from the battery cells and modules. Company F highlights that this is typically done using specialized cleaning equipment and techniques to avoid damaging the sensitive internal components of the batteries and to prevent both environmental contamination and worker exposure to harmful materials. In some cases, the EVBs might follow a conditioning process to eliminate any remaining charge or energy stored within the cells. This procedure serves to mitigate safety hazards during handling and internal transportation, as well as to prepare the batteries for subsequent testing and assessment.

Charging / Discharging

To ensure that the SoC is always in the correct or “optimal” state, the process of charging and discharging may be repeated multiple times during the return flow. The interviewed companies stated that this may happen because of battery charge degradation over time and natural decaying of the battery charge levels. Additionally, to changing the energy charge level, Company E stated that the charging process also enables technicians to gather accurate data on the batteries' energy storage capabilities, cycle life, and efficiency. According to Company A, charging and discharging of the battery is inherent to the return flow, however, it is during this moment that the process of “balancing” is done, resetting the battery’s internal cells to a more neutral state, which can be able to greatly increase the performance and improve the lifetime. Uzair et al. (2021) defines that during the balancing charge, the BMS carefully monitors and regulates the charging process, ensuring that each cell within the pack reaches an optimal state. This involves redistributing charge among cells to equalize their SoC levels, effectively mitigating any discrepancies that may have arisen over time (Uzair et al., 2021).

Company A complements that the process typically begins by charging the entire battery pack to a predetermined voltage level, bringing all cells to a baseline state. Then, the BMS selectively channels additional charge to cells with lower SoC until uniformity is achieved across the pack. This iterative process continues until each cell reaches its maximum capacity without overcharging, safeguarding against potential damage. By implementing a balancing charge step connected to the charging and discharging of the batteries in the BRC, it is possible to maximize the performance and lifespan of their batteries in second life applications. Not only does it optimize energy storage capacity, but it also enhances safety and reliability, ensuring that these batteries continue to serve effectively in their new roles beyond the road.

Companies also reported that after processed and stored to wait for their final destination, it is necessary to monitor battery charge levels to ensure that big drops are not happening, which could damage the battery internally or prevent it from properly performing afterwards. This means that if a problem is identified, the batteries may need to be taken from stock and brought back to charging stations.

Diagnosing / Testing

Following in the flow, the next step is to perform testing on the EVBs to make a complete understanding of their internal components, health, and performance. This process is usually conducted by experienced technicians and supported by sophisticated diagnostic tools and software. However, there was no consensus on the interviewed companies about either what should be investigated or the amount of EVBs in the flow that would undergo the testing. For example, Company A reported on performing complete and comprehensive assessments on random EVBs mostly due to two factors. First, the amount of information carried on the BMS plus the ones acquired from the charging / discharging step would be enough to make decisions on the battery's future with a good level of confidence for their business. Secondly, the testing step requires specialized equipment that runs readings in the batteries during long periods of time that could range from 4 to 8 hours, depending on their complexity. This then represents a huge bottleneck in the process, and it would be a dealbreaker in their operation to perform testing in all batteries, therefore the random testing is used to enhance their decision making based on the BMS and electrical charge information. On the other hand, Company C is testing 100% of the batteries that went into the process for any second life strategy, except for critical batteries. In their experience, this gives them much more precise information about the batteries that they are getting, and it also opens opportunities to improve their final products' value. Additionally, Company C also stated that they were able to greatly improve the time for testing each battery through experience and the development of a proprietary system that is used in connection to the testing equipment, reducing the time of each testing to as low as 40 minutes in the best scenarios.

Once the diagnosing and testing of the EVB is complete, the data collected is analyzed to make informed decisions regarding the suitability of the EVB for its intended second life application, based on the preferred decision flow that each company has. Usually, batteries that meet the required performance criteria can be then prepared for repair, refurbishment, and remanufacturing, that still represent the best return on investment to the companies. But they also may go directly to repurposing, for companies that are focusing their business in the creating of ESSs, for example. Nevertheless, in a general understanding among the interviewed companies, those EVBs that fall short in the testing and do not possess enough potential for other applications end up going through the recycling processes to extract valuable materials and components.

Storing

Before EVBs transition into their second life applications, it is highly probable that they will have to stay some time in storage to wait for an order, the building up of a lot or a truckload, or simply to wait for shipping preparation. However, this is a crucial step that can have an impact on the battery's integrity. The difference among the interviewed companies is not considered relevant, as all of them reported strong logistical practices, use of integrated technology (Warehouse Management Systems – WMS) and following the ample regulations covering this matter. The biggest concern is related to ensuring the safety of the storage area environment, which requires that the EVBs should be placed into isolated packages to prevent self-discharge and ensuring that the batteries retain their charge for extended periods. While also helping on safeguarding against external factors such as temperature fluctuations, humidity, and physical damage, which can all impact battery health. Climate-controlled storage facilities using fans and exhausters are also a common practice, providing a closer to ideal environment for EVBs preservation. These facilities maintain stable temperature and humidity levels, mitigating the risk of degradation caused by extreme conditions. EVBs are often stored in racks or containers designed to provide physical support and protection, minimizing the potential for damage during handling and transportation.

Moreover, all companies stated that there are time limits for the storage of the batteries in their facilities, ranging from 90 to 180 days, which can be defined by either a local regulation or by internal standards. Yet, according to Company B, the current state of the market is making the average storage time to be way smaller, as the current demand is higher than the number of batteries at the end of their first life that they are able to source. Even so, all companies in the study have processes in place to monitor the batteries. Periodic inspections and testing help track the health and condition of the stored EVBs, allowing technicians to intervene if any issues arise. There is a focus on safety and, for example, monitoring temperature levels and having contingency plans in case of spikes that could lead to fires. In addition, batteries may undergo partial recharging to maintain optimal performance and readiness for deployment.

Shipping

Safety protocols play a central role in the shipping of EVBs. All companies reported compliance with either international regulations, such as the UN Model Regulations for the Transport of Dangerous Goods, or their local government regulations, like Regulation 2023/1542 for the European Union. Either way, the essential point is to ensure the safe handling and transport of EVBs. Company D explains that proper labeling, documentation, and packaging are critical aspects of regulatory compliance, helping to mitigate potential hazards and ensure transparency throughout the shipping process. Moreover, coordination with transportation providers experienced in handling hazardous materials is a key to the successful transportation of products that are labeled as ‘dangerous goods’, such as EVBs. Company E highlighted that on building up partnerships for the transportation of the batteries, it is very important to consider if these providers have the expertise and equipment necessary to navigate regulatory requirements and safely transport EVBs or repurposed solutions to their destination. Company F adds that environmental responsibility should also be a priority in the shipping of EVBs and that internal efforts are necessary to minimize the carbon footprint associated with transportation by optimizing logistics routes, maximizing load efficiency, and utilizing low-emission vehicles where possible.

Challenges / Bottlenecks

As expected on new and emerging markets, many of the challenges highlighted by the companies are connected to the lack of standard practices in the industry, the high variability of products, and the uncertainty regarding possible new regulations. For instance, Company C stated that their biggest challenge is to make their transportation partners to comply with their internal standards and expectations, while having to implement many specific processes to handle their products both in the inbound and outbound logistics. This is generating a negative impact on the efficiency towards their suppliers and customers, but also on their capacity to expand at the rate they would like to.

The lack of standardization also extends to the batteries themselves, with many different manufacturers, models, generations, and capacity, the compatibility among EVB models poses a significant bottleneck for second life strategies. Company B shared that this may not be a big problem for repairing or recycling, but it can be challenging to repurpose batteries across different platforms, due to the fact that different manufacturers use varying battery chemistries, form factors, and communication protocols. They highlight that standardization efforts over the whole industry are needed to develop common interfaces and compatibility standards to facilitate the integration of EVBs into diverse applications.

Lastly, the uncertainty about new regulations was also underlined as a challenge that companies must face to survive in this business area. Company F reported that bigger companies may have the ability to adapt at a faster pace to comply with the new regulations, but for smaller companies, like themselves, this represents a big investment of time and money and can be a blockage for new players that could otherwise be heating the economy, increasing the competitiveness, and helping in the development of new technologies.

Success Factors

Although directly connected to one of the challenges, it was also a common sense among interviewees that a critical success factor is the collaboration among stakeholders across the electric vehicle ecosystem, which was classified as being essential for the success of second life initiatives by Company E. Company A also described that building partnerships with battery manufacturers, integrators, end-users, and regulatory bodies fosters knowledge sharing, resource pooling, and collective problem-solving. Collaborative efforts accelerate innovation, promote best practices, and overcome barriers to adoption, driving the growth of second life strategies.

Likewise, conducting a thorough assessment of EVBs seems crucial for identifying suitable candidates for second life applications. Company C believes that a comprehensive evaluation of battery health, performance, and degradation levels helps determine the second life strategies options that can aggregate more value and return on investment for the organization. Company D added that by performing advanced diagnostics and testing methodologies they are able to have a more accurate assessment, ensuring that only high-quality batteries enter the second life ecosystem, which can be a competitive advantage for them. Finally, on a general level, all interviewed companies agreed that for being positioned on a volatile business, demonstrating economic viability, and developing sustainable business models are critical for attracting investment and scaling their second life initiatives.

4.2.3 Influencing factors

There are external and internal factors extracted from the concepts discussed in this work Literature Review and gathered from the Companies' interviews that can influence in the design and construction of a framework for a BRC. The concepts were previously presented in Figure 2.3 and will be discussed in the following sections.

External factors

The *Regulatory and Policy frameworks* is a theme constantly present in all explorations done for this thesis work, either on the academic side or on the practical information acquired from the participant companies. The local governmental rules and international laws guide the limits of the companies' operations and create the landscape for their innovations. EU Regulation 2023/15424.1.3 has been extensively investigated and an overview of its impact on the BRC capabilities can be found in section 4.1.3. This was done because this specific regulation is the currently active regulatory framework for all countries in the European Union and it has a direct influence on the proposed design that is going to be presented in section 4.3. It is important to highlight, however, that not all aspects of the BRC operation are covered under this regulation and capabilities such as 'sorting', 'pre-diagnosis, and 'cleaning' can be either too generic or too specific and therefore are not cited.

The uniqueness of the local regulations has also been discussed with companies from different countries, but most of them expressed that they are on the attempt to create a process that can be easily adjusted to follow the rules of other regions. Furthermore, Companies that are not originally from the EU region still recognized the importance of the European regulation for their business' expansion.

Other aspects that will directly influence the design of a BRC framework are the *Industry Best Practices*, put together on section 4.2.2, and that are used as main source of information for the practical understanding of how the capabilities are connected and relate to each other. Many smaller and sensible details are being extracted from this source of information such as, for example, the testing process described by Company C. This is a critical step in the process, usually described as a bottleneck, and to perform in-depth testing on all batteries enables the building of a strong net of information that leads to make more assertive decisions on their current flow, but also to create and store historical data that will be of great importance for their research and development of new processes, methods, and technologies. Likewise, Company E also has a strong testing focus in their flow, but their objective is leaning to improve the testing capabilities and making it more accessible and replicable to all return flows that they plan to develop in the future.

On a more general level, it is also possible to highlight that EVB second life business area still has much to develop and to mature. This means that several *Business Opportunities* lie ahead for companies that are willing to take the risks and invest in solutions for the future of EVB solutions. Company E, for example, informed that R&D is currently one of their biggest focuses for the next 5 years, and they expect that this investment will place them on a strategical position in South America as the flagship company for second life EVB solutions for vehicle owners and manufacturers. Likewise, Company D approach is very similar, although their focus being primarily to the recycling of EVBs, they expect to take the current technologies to a next level of efficiency and become a reference for the material recovery of rare metals.

Internal factors

In the current business environment, *Logistical Challenges* are inherent to the reverse logistics flow of EVBs. They are not considered a consequence of an uncertain nature, but represent disputes, demands, or problems that are likely to persist in the market. From both the literature review and companies' interview the call for standardization of processes along EVBs return flow is a recurring theme. Dunn et al. (2021), Gu et al. (2024), and Slattery et al. (2021) highlight the importance of standardized EVBs design, shape, and size to streamline return flow activities, such as collection and recycling. It was previously described that Company B works closely to OEMs to improve EVBs design for recyclability. This initiative can be echoed in various aspects of the supply chain, such as the incompatibility of EVBs with standard pallet sizes, leading to wasted space in trucks. While Company B advocates for superior standards among all players in the supply chain to improve efficient utilization of space and time to achieve sustainable levels of cost-effectiveness. Consequently, third-party logistics providers should also engage in discussions with battery OEMs and EVBs second life solutions providers. Moreover, it was also found that Volvo Group understands that the standardization of information should also play an important role in creating a strong BRC flow, as will be discussed in the next chapter.

Another factor to be considered is that the expenses related to transportation, storage, packaging, and recycling are considerably high. All interviewed companies highlighted that the integration of reverse logistics into the supply chain should be managed cost-effectively. However, due to the market's immaturity, the costs currently outweigh the benefits. On the opposite direction, Company E argues that, currently, the return logistics processes are much more efficient for the lead-acid batteries market, with a very high rate of recycling in Europe, demonstrating the potential for also developing an effective supply chain for EVBs. Moreover, the costs associated with reverse logistics processes are elevated due to the limited infrastructure. This poses challenges for third-party logistics providers in consolidating EVBs, often facing the problem of having to transport a single EVB (as noted by Company A, and Company B). This challenge is closely linked to the vehicle routing problem discussed in section 3.5, which revolves around optimizing the coordination of truck fleets to maximize efficiency.

Lastly, Volvo Group is also internally influencing the development of a BRC framework and stated very ambitious *Sustainability Goals* for the upcoming years. Volvo Group is actively working towards its electrification goals with a focus on decarbonization, science-based targets, and a transition to electric vehicles across its operations (Volvo Group, 2024). The Group’s sustainability report explains that the ambition is to drive decarbonization, affecting all aspects of its operations, including sourcing, logistics, research and product development, production, sales, and cooperations. At the same time, it is actively working on transitioning its operations to include electric trucks, buses, construction equipment, and drivelines. A BRC can be seen as an integral part of this transitions process, which will enable the boost on selling new electric vehicles, while having a sturdy return process that will assure increased profitability and sustainability. Furthermore, it is also stated that even if it is challenging to predict the transition pace or technology preferences in the longer term for specific markets or regions, Volvo Group aims to drive transformation in business segments where it is active, regardless of the expected pace (Volvo Group, 2024). Likewise, even if the current volumes of returning EVBs after the ending of their first life is not enough to create a lucrative business, now is the time for investing in building up the infrastructure that will serve as basis for the future.

5 Results

The following sections are written to present the main findings for the application on Volvo Group and a general overview of the three research questions, explaining the reach of the existing literature and highlighting this research's contribution to the state of knowledge. Finally, section 5.3 will present methodological reflections from the author.

5.1 Potential design for Volvo Group BRC

In this section results for *RQ3* are presented. First the Volvo Group case is introduced. Then, based on the workshop described in section 2.2.4, the current reverse logistics flow situation is described and opportunities for improvement identified. Finally, a potential framework for a BRC considering the previously explored capabilities from *RQ1* and the information generated by the author based on the findings from *RQ2* are presented.

5.1.1 Case description

Volvo Group is a Swedish multinational manufacturing company that specializes in trucks, buses, and construction equipment. It encompasses fourteen business areas: Volvo Trucks, Volvo Buses, Renault Trucks, Mack Trucks, Volvo Construction Equipment, Eicher Motors, Volvo Financial Services, Volvo Autonomous Solutions, Volvo Energy, Volvo Penta (a supplier of marine and industrial drive systems), SDLG (construction equipment in North America), Rokbak (manufacturer of haulers), Prevost (manufacturer of motorhomes), and Novabus (manufacturer of electrical buses). Currently, the Volvo Group has a strategic focus on three key areas: connectivity, automation, and electrification. Of these, electrification is particularly emphasized, especially in the European Union, due to the CO2 emission performance standards set for 2025, 2023 and 2050 (European Commission, 2019; European Commission, 2023).

In its pursuit of electrification, Volvo Group has introduced a range of innovative products over the years. The journey began in 2009 with the launch of hybrid electric buses and trucks, powered by high-power LIBs. Subsequently, in 2016, Volvo Group unveiled its first plug-in hybrid electric bus. The company made significant progress in 2018 with the introduction of its first fully electric buses, equipped with LIBs boasting a balanced power and energy density. In November 2019, Volvo Trucks made headlines by introducing fully electric medium-duty trucks designed for urban transport in select European markets. Historically, Volvo Group has found success in truck markets, particularly in Sweden, Britain, Germany, and France, while its bus sales have been concentrated in Sweden, Norway, and Poland. Since its foray into electric vehicles, Volvo Group has seen considerable success, with over 5,000 vehicles hitting the market to date, of which 1,977 only in 2023. The European Union (EU) accounts for the majority (90%) of these sales, with the United Kingdom and US emerging as important markets for Volvo Group's EV offerings.

Volvo Group manufactures the energy storage control module in-house, while LIBs are presently sourced from various suppliers. In 2019, Volvo Group formed a strategic alliance with Samsung SDI to enhance its capabilities in electromobility. This partnership involves Samsung SDI supplying battery cells and modules to Volvo Group, as well as sharing battery pack technology for in-house assembly within Volvo Group's manufacturing facilities. The collaboration underscores Volvo Group's commitment to expanding its expertise and integrating more battery production internally. Also in 2019, Volvo Group has partnered with the Swedish Electric Transport Laboratory (SEEL) to enhance knowledge-sharing and collaboration in advancing electromobility. Their aim is to foster the development of a sustainable and competitive battery value chain, both within Sweden and across Europe. Another example is the partnership signed in 2023 between Volvo Construction Equipment and CRH, the global leader in building materials solutions. The strategic collaboration will concentrate on electrification, charging infrastructure, low carbon fuels, and renewable energy, collectively possessing the potential to reduce emissions. Volvo is dedicated to supporting its customers in setting a precedent through partnerships that demonstrate the effectiveness and efficiency of electric solutions.

Currently, aftermarket services and recycling solutions for EVBs are addressed on a project-by-project basis due to the diverse battery chemistries and suppliers involved. However, Volvo Group anticipates a trend towards standardizing their battery technology solutions in the future, prompting them to pursue a more global and proactive approach. Historically, Volvo Group has incorporated repair, refurbishment, and remanufacturing of components into its business model for conventional trucks and buses. However, with EVB production currently outsourced, Volvo Group heavily relies on knowledge exchange with suppliers for aftermarket activities and must assess the feasibility of these arrangements. Furthermore, Volvo Group also started the plans to produce their own battery packs in Ghent’s truck plant from 2025 and battery cells from 2029 on a brand-new battery production plant in Mariestad.

While no official and standard BRC is currently in place, a program to develop the processes related to this location was initiated in early 2024. A central strategy is essential, particularly for Volvo Group as a light and heavy-duty vehicle manufacturer, as they are likely to receive LIBs earlier than other passenger vehicle OEMs. This should happen given the total lifetime of EVBs for passenger’s cars being around 40% longer than heavy duty vehicles (Tankou et al., 2023), the time between the sale of an electric bus or truck and the return of end-of-use or end-of-life LIBs will be significantly shorter compared to small cars. Although Volvo Group currently receives a relatively small number of returning EVBs, this is expected to increase substantially between 2025 and 2030.

5.1.2 Current EVB Reverse Logistics flow

Nowadays, the return flow of EVBs is basically done for buses and trucks’ used batteries. This flow can be activated by EVBs that are faulty (under warranty or not), not suitable (low performance), or on early retirement (battery upgraded to new generation or simply replaced for better performance). In all cases, however, Volvo Group’s dealers are the point of initial analysis and collection of these used EVBs. This is done to ensure better control, traceability, and service level to both Volvo Group and vehicle owners, while also safeguarding a better integration for the whole supply chain.

When an EVB is returned to a Volvo dealer, it undergoes a reading of the BMS to create a report for the batterie’s SOH and SOC, that are then transmitted to a database. The customer gets their replaced battery, and the old one is returned to Volvo’s powertrain production plant in Skövde. If the battery is under warranty, it is directed to the manufacture’s facility for investigation and to be repaired, refurbished, or remanufactured. If not, technical experts at

Volvo will assess the necessary repairs or start preparation for second life applications. Recycling is also an option for batteries in critical state or even for non-critical ones that are found to be unfit for any other kind of second life applications. The recycling process, however, is done on a separated flow by taking the batteries to recycling partners that can receive the battery from different points of the return flow. Nevertheless, all processes and decisions are being made on an individual level for each battery that enters the return flow, which is leading to a time-consuming and complex process. This tends to become even more aggravated as the volume of EVBs in the return flow starts to grow. Consequently, Volvo Group is aiming to optimize end-of-use and end-of-life activities by assessing the feasibility of repair, refurbishment, remanufacturing, repurposing, and closed-loop recycling, thereby improving sustainability across the EVB lifecycle.

After analyzing Volvo Group's current situation and insights from *RQ1* and *RQ2*, Table 5.1 outlines several improvement opportunities identified during the workshop to enhance the future implementation of a BRC framework. Understanding how the capabilities of a BRC connect to each other and play a pivotal role in the return flow is crucial for identifying the most suitable BRC framework design. Interview findings suggest that the most crucial steps in the return flow start at the very beginning, with the partnership with transportation companies, goes through the testing of the batteries and the preparation for second file. These aspects can greatly influence Volvo Group's design on how EVBs will flow from one step to another, benefiting from the strong existing supply chain, the know-how from close-related battery manufacturers and potential partnerships on creating second life solutions.

Table 5.1 - Opportunities for improvements at Volvo Group

Step	Opportunities for improvement
Return Flow	Using current network that links dealers to Volvo locations
	Enforce Volvo standards on regulations, safety, and security
	Combining volumes to increase efficiency and decrease costs
Testing	Accessing information for the whole life of the EVB
	Using dealers' testing capabilities to improve reliance
	Developing new and faster solutions for testing and diagnosing
	Improving current processes through OEMs proximity
	Benchmarking on batteries' manufacturers
Second life preparation	Researching on new and profitable solutions
	Exploring new partnerships
	Designing a closed flow to increase profitability in the long term

5.2 Ideation of potential BRC model

Volvo could implement a complete BRC infrastructure to attend its future needs on the return flow of EVBs, however, with the exploration done in this theses work, the insights from Volvo employees, and the trends in volume being expected to grow over the next few years, the author proposes that the basic and advanced capabilities should be implement in two different phases.

Phase one (short term)

At the beginning, implementing only the basic capabilities in the short term (receiving, inspection, sorting, and shipping) can be seen as having two major benefits. First, it can organize the current processes that are being performed on individual level for each EVB in the return flow. That way, Volvo can focus on improving the return flow and strengthening its relations with the dealers. It can also represent an opportunity to work on the flow of information that is generated on the BMS readings at the dealer side and on the database formation that all the information should be stored on. Moreover, it is an opportunity to build up a solid logistical foundation of processes to support the implementation of the later advanced capabilities.

Secondly, it can serve as a business case to gather learnings and expanded information for a smoother transition and better implementation of phase two. A BRC implementation is a new endeavor for Volvo Group, but the amount of available information that could lead to better preparation, as it became clear in section 4.1, is scarcely available. Therefore, Volvo will need to create its own knowledge, which will be necessary for adapting the existing BRC capabilities in the industry to their own scenario and to fit their own objectives. This means that any amount of information that the group can acquire prior to the investments that shall be made will be beneficial in leading them to conducting better projects and ultimately achieving success.

As a result, the basic capabilities then can create a streamline of returned EVBs that will be received and processed using the existing logistical infrastructure. It is important to highlight that although the transportation of the EVBs from dealers to BRC not being considered one of the capabilities, it is still critical to have a strong and standardized process in place that also takes all the regulation in consideration. Also, the current EU Regulation should be applied for all transportation in the return flow, from dealers to BRC and from BRC to final destination (European Union, 2023, Annex XIV). Later, the EVBs will be inspected to evaluate the physical integrity and if the information registered in the system matches the displayed information in the battery pack and documentation. Any deviations in this step must have an associated contingency plan so that the operators know how to act and remediate as needed. EVBs can then be sorted and shipped to their intended destination, namely Warranty flow; Re-use or Repair; Refurbishment, Remanufacturing, or Repurposing; and Recycling. This means that batteries will enter the return flow with a set destination based on the SOH and SOC that they had in the last reading at the dealers and the BRC will act as a transition of this batteries, from the collection to the Volvo internal or external partners. Figure 5.1 is illustrating the basic capabilities flow under a blue-dotted line.

Phase two (long term)

Upon development and experimentation on the basic capabilities, the implementation of the advanced capabilities in a longer term should take place. The first one being the pre-diagnosis, which happens just after the sorting of the batteries. This step is intended to be the link between the basic capabilities and the rest of the process. EVBs shall be examined on a more detailed way and having their initial second life destination checked and confirmed. This is important for not adding value to a battery (for example by cleaning the external pack) that should actually have their components recycled. Then, if the recycling of the EVB is done locally, the BRC can also be responsible for the dismantling of the battery pack, to avoid the internal movement of the big and heavy assembled batteries. That way, the BRC can optionally integrate a step to dismantle and clean the batteries' internal components for them to arrive segregated and pre-processed to the recycling location.

Moving forward, the cleaning of the EVB's pack should take place. As described by most companies participating in this study, this step should be simple, but effective. The external parts of the batteries must be clean of debris, oil spilling, dust, and any blockage in the connectors, but this should be done mainly without the use of chemicals substances to avoid contamination of the battery's components. Although very straightforward, the cleaning of the EVBs is adding value by giving the battery a better look and enhancing the possibility of technicians identifying physical damages that could be addressed, while also making sure that this battery will be on a good shape for its second life application.

A combination of the capabilities 'Charging/Discharging' and 'Testing' of the batteries shall take place after they have been cleaned. As described in section 4.2 there is no consensus among the industry on the percentage of batteries on the return flow that should undergo a complete test, and even on the depth of this examination. However, on the author's evaluation, it should be more beneficial for Volvo to create a return flow that perform in-depth testing on all EVBs to primarily guarantee that each battery is being designated to the better second life option, which means having more lucrative decisions or even strategical decisions that may be immediately more expensive, but matchets the group long term ambition. On an indirect basis, this process can also be used to create a very robust data basis of batteries' history, SOH, energy cycles, ownership specifics and much more. This data can feed the BRC process itself, but also be connected to other areas, projects, or initiatives from the whole Volvo Group. It is understandable that designing a process to test all batteries can be time consuming and create a clear bottleneck, however, Volvo Energy is already investigating alternatives to significantly decrease the time to test their batteries either by using new technologies or by improving the current one.

As described, this should be a block in the flow responsible also for charge and discharge of the batteries, which can happen either before or during the testing of the batteries. Even if this block represents a crucial step in the BRC process, there are a few key points that should be taken into special consideration. First, the charging and discharging of the batteries is not responsible only for taking the charge level to the range chose by Volvo, but for performing the *balancing* of the battery cells, to ensure the maximization of the performance and lifespan in the second life applications. Second, the minimum amount of information extracted from the testing process should be in line to what is described in the current EU Regulation specifications for the testing of batteries in preparation for second life applications (European Union, 2023, Annex VII). Third, the testing process should be designed with some level of flexibility, given that the potential customers for the product that the EVBs will become can have different requirements in terms of information (being more or less detailed), and Volvo should be ready to provide adapted information to different situations.

For the storing capability it is worth mentioning that Volvo Group already have infrastructure and experience in storage of used EVBs due to the current set up that is running in the company. Nevertheless, two points can be improved from the descriptions given by the interviewed companies. First, the temperature and humidity are usually controlled by using fans and exhausters. Even though these solutions seem to be cheap, the companies stated that this is an effective and reliable way to provide the warehouse area with the safety standards that are required for this kind of operation. Secondly, it is important to have a process in place to monitor the charge level of the batteries over time and to take preventive (or even predictive) actions to recharge batteries whose charge may have dropped too much. This can guarantee that the correct range of charge is being maintained by the stored batteries, preventing premature degradation or other problems associated with uncontrolled charge levels. Additionally, all the storage space and operation that involves LIBs must be following the guidelines present in the current EU Regulation for storage and treatment requirements (European Union, 2023, Annex XII).

The last capability in the advanced flow is the preparation for the second life application, as the last step inside the BRC, the EVBs shall be picked, revised, combined, and prepared for shipping. In this step batteries must go through a checklist of regulatory conformities to guarantee that they are in the correct package and carrying the correct labeling as described in the current EU Regulation for labelling, marking and information requirements (European Union, 2023, Annex VI). Moreover, batteries that are destined for repurposing can be pre-assembled to facilitate the transportation to, for example, an ESS assembler and to ensure that the same battery types, models, and capacities are being connected. Lastly, although not in place until 2027, the battery passport already has its parameters defined by the EU Regulation and their early implementation by Volvo can be seen as a vantage point from a strategic perspective and a drive towards sustainability that matches the company's objectives (European Union, 2023, Annex XIII). Figure 5.1 is illustrating the advanced capabilities flow under a green-dotted line.

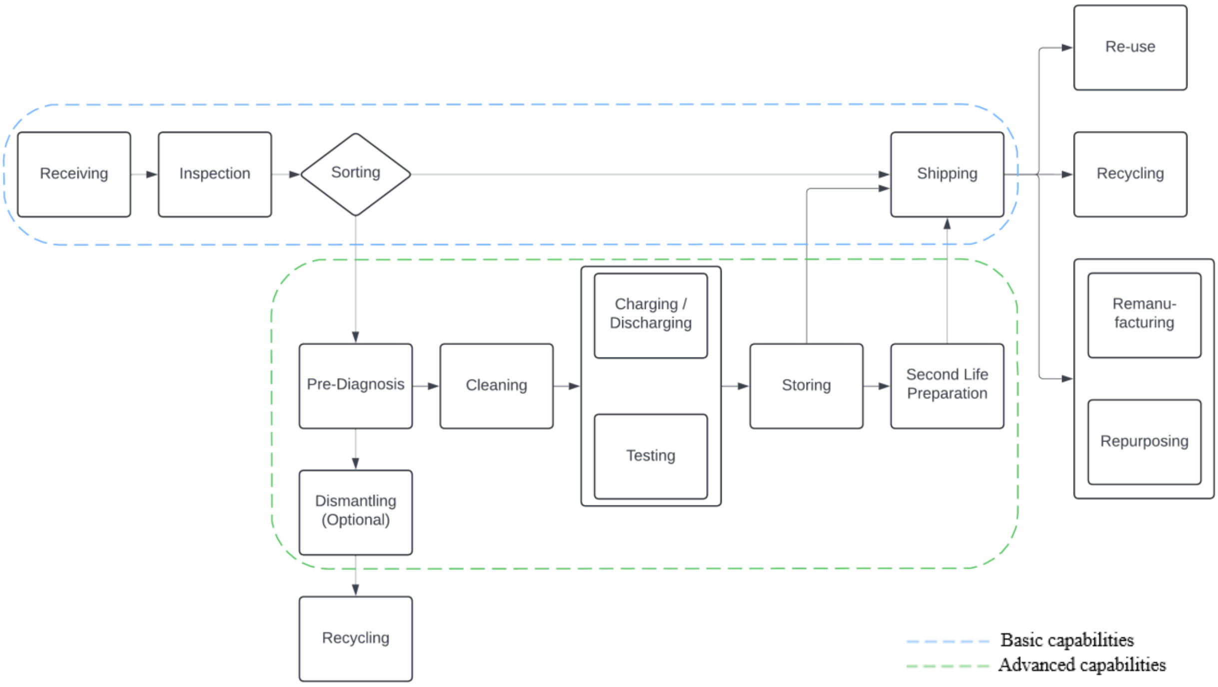

Figure 5.1 - Potential BRC framework for Volvo Group

5.3 Overview of the findings and their significance

This thesis aimed to investigate how companies could build up and implement a Battery Return Center, ensuring scalability and reliability to the return flow for the second life of EVBs. This aim was approached by identifying the capabilities to operationalize a BRC (*RQ1*), exploring current approaches used by reference industry, their business strategy, and primary influencing factors (*RQ2*), as well as designing a potential BRC framework for implementation at Volvo Group (*RQ3*).

5.3.1 BRC capabilities

There is a clear trend in modern logistics of EVBs for sustainable solution on shifting from a linear towards a closed-loop supply chain, that adopt the strategy of CE practices and emphasize on maximizing the lifespan of existing products or components, while minimizing the necessity for new battery production. Although many of the capabilities for a BRC explored in this study are not originally together, by combining this knowledge was possible to create a clear path on the return logistics of EVBs that are destined for second life applications. Thus, the optimal return flow strategy involves creating a design for the processes prioritizing activities that prolong the lifecycle of the product or components for as long as it is feasible and respecting the regulations. This study's contribution lies in proposing a BRC design for the return flow of EVBs that encompasses all essential capabilities for companies to create a flexible and scalable second life solution. The suggested design of the BRC aligns with the regulatory aspects outlined in the Regulation (EU) 2023/1542 and merges the current knowledge foundation with the best practices in industry. Additionally, it confirms the commonly held belief that EVBs can be seen as a promising technology for the application of CE strategies that create a sustainable option for future economy.

The interpretation of the proposed BRC design should also take into consideration the limitations outlined in section 2.5, as some uncertainties persist regarding the assumptions made. While the findings provide insights into the return flow process, such as the importance of the close integration to 3PL partners, it is still susceptible to a deeper investigation on determining the aspects that are crucial for increasing or decreasing the chances of a successful BRC implementation. Although a more sophisticated and adaptable assessment might yield slightly different results, it is still projected that the outcomes should remain consistent. Consequently, despite their constraints, the existing studies can still offer valuable guidance for decision-making purposes.

Moreover, considering the uncertainty around the themes explored due to the young age of the topics under evaluation, a possible short-term trade-off can be observed on the implementation of the proposed BRC design. As the return flow of EVBs can be too complex in their individual steps, by adding a BRC in the terms proposed in this study, companies can have an adaptable and scalable process in line with best practices and regulation. This may enable them to focus on their individual capabilities to create improvements and technological advancements, potentially creating unique solutions and consolidating many of the unknown aspects in the return flow. The current and potential new regulations are another characteristic that require constant attention due to the impact that they can have in altering the standards and the guidelines that companies must follow. Even the current Regulation (EU) 2023/1542, that was used as reference for this study, is still not completely implemented and is subject to changes that may impact the structure of a BRC.

Some of the capabilities are clearly more explored in literature, such as inspection, charging/discharging, and testing, where the use of different sources was possible to create a stronger basis of information and understanding for better placement of the capability in the flow and to create connections around it. On the other hand, the capabilities pre-diagnosis and second life preparation are not fully explored in other academic works, therefore some other smaller aspects or activities were put together by the author for the creation of those steps in the internal process of a BRC. Additionally, the coverage of the capabilities by the current EU regulation is also not balanced, ranging from very detailed descriptions (such as for shipping) to no citation, which is the case for the sorting capability.

Overall, it remains a strategic decision of companies either to adopt the present perspective for dealing with the return flow of EVBs or to create a custom-made solution that is entirely designed to their environment. However, the problem under discussion in this study will be a reality for all companies that are in the business of offering solutions for the second life of EVBs. Hence, basic and advanced capabilities can be combined to provide the flexibility and adaptability for navigating into the challenges that this industry is imposing.

5.3.2 Best practices in the industry

The findings establish that companies can share several similarities in building up their return flow, but at the same time have very distinct strategies or operations. This diversity in their activities highlights that the challenges that each company face may differ from each other, but also that the market niche that they fit into may also be slightly different. Simultaneously, it demonstrates that the return flow formulation among many organizations tends to be more reactive than proactive. This tendency could be attributed to significant uncertainties surrounding technological advancements, regulations, and the economic viability of various second life strategies for EVBs. It may also suggest that there is a close relation to innovation in this business area, where companies try to propose different solutions for the same problems.

While companies can have different focus on which second life solutions they implement, there is a clear trend towards repurposing and recycling for the companies participating in this study. However, repairing and remanufacturing are still essential for filling all gaps in demand, whereas being very good economic options that extend the batteries’ lifecycle, which is usually an essential factor for reaching their sustainability goals. Furthermore, as pointed out by Company D, repairing and remanufacturing of EVBs tends to be done internally by the vehicle manufacturing companies or by their EVB providers, due to the particularity of each model and the warranty processes.

The operationalization of the logistical return flow was found to be a key aspect for understanding the transition of EVBs from first to second life, emphasizing expertise, innovation, and partnerships within the value chain to manage returned EVBs effectively. But the interviews also aimed to understand how participant companies manage EVBs throughout their lifecycle and their strategies to foster CE on a higher level. All companies emphasized innovation and sustainability as core values and highlighted that maximizing the EVBs lifecycle is considered a guideline on how they build their processes and drive their business, even if they have differing approaches. The findings revealed that there is no standard way of creating the return logistics of EVBs, but each company seems to operate on an adapted mode from a similar business or simply started to use a network that was already in place for another purpose.

A similar outlook was found for the processes related to the BRC capabilities. Which means that there is no ideal single way to create the steps that link first and second life. This confirms the findings of Shahjalal et al. (2022) and Ferrara et al. (2021) according to which the strategies, the operationalization, and the activities for enabling the second life of EVBs are highly dependent on contextual factors. Furthermore, in many cases capabilities such as receiving, storing, and shipping have a strong influence of existing logistical setups that companies have in place but were adapted to comply with local regulations, however, companies that were born in the EVB business may have an upper hand by creating flows designed specifically for dealing with the challenges of this area. Lastly, the capabilities that are more technical, as for example charging/discharging and testing, present many specificities between different companies as their individual experiences have a strong contribution on their view of an effective, efficient, and profitable return flow. In conclusion, all the variability in the capabilities represents the need for a highly flexible operation that can adapt itself for different situations, especially when considering that the end solution companies are selling can be different, regarding the second life strategy that the chose to follow.

The results further highlight that some influencing factors have a direct impact on the potential design of a BRC. On one side the external factors are connected in great part to the regulatory and policy frameworks that act on the activities of the return flow. This was underlined by all companies that participated in the study and confirms the findings expressed in Martinez-Laserna et al. (2018) and Gu et al. (2024), that stresses the role of complaining to regulation as one of the aspects for the success of EVBs' second life. On the other side, the internal factors are strongly driven by the logistical challenges inherent to the business, and to which many companies pointed standardization of internal and external (from 3PLs) processes as a turning point for the enabling of scalability and operational cost reduction. But also, Volvo Group's sustainability goals that play a crucial position in setting long term objectives and enabling investments that aim to solve present and future problems.

5.3.3 Application in Volvo Group

Within the context of Volvo Group, a combination of the findings from *RQ1* and *RQ2* were used to create the proposed design presented in section 5.1. However, this was an organic process developed over the twelve weeks that the author was inserted into the Volvo Energy environment. Several opportunities for improvements were unveiled during this process and the collaboration of Volvo employees was crucial for the development of a functional design. If the BRC is considered from an operational perspective, many specific and smaller activities, tasks, or technical details are not present in the discussion made in this study, due to either time or scope limitations. Nevertheless, the capabilities are considered to be flexible enough for being adapted to different internal needs that may be considered important. Which can be seen as an advantage from Volvo's perspective, but also from outside organizations that may find the results presented in this study to be useful for their context.

As previously presented, the BRC is intended to be the connection between EVBs' first and second life. Specifically, this step on the return flow can increase Volvo's capacity to deal with the expanding return of EVBs after their first life in the upcoming years, while also upgrading the quality and value of returned batteries (e.g., cleaning, testing). Additionally, the BRC enables the creation of decision mechanisms that improve the ability to shift between different strategies in many ways. For example, by buffering the return process Volvo Group will have the possibility to choose between a more profitable flow, which could mean focusing on reuse and refurbishing to increase aftermarket supply. Or following a flow destined to develop customer service level, such as selling batteries for ESS assemblers. Or even to increase adherence to regulatory requirements, which could mean focusing on material recovery for boosting battery production.

Lastly, the proposed two-phase implementation is intended to provide a feasible and adaptable experience for the current scenario of Volvo Group. However, it is worth noting that the complete flow of capabilities can be implemented all at the same time, without any losses to the logic utilized for this study. This is also true for the general concept that can be adapted for applications in other organizations and scenarios.

5.4 Methodological reflections

This thesis carefully focused on return flow and capabilities adopted by a range of companies that provide solutions focused on the second life of EVBs, assuming that they are the ones shaping this business area, alongside Volvo Group. Consequently, other OEMs (such as battery manufacturers) and other major automotive companies were methodically excluded. While mapping all industry's perspective could have offered a broader perspective, the thesis aimed to explore EVBs return flow operationalization and opportunities in EVBs lifecycle strategies, successfully achieved through its research design. Although the final BRC design follows the EU regulation guidelines, some of the companies that participated in the study gave the author the opportunity to understand similarities to regulations from other countries and highlight them in the text.

Additionally, some trade-off had to be made between the breadth of the EVBs second life solutions, which networks all second life strategies, and the in-depth exploration and explanation of the processes only directly connected to a BRC. This cutout could affect the applicability of findings for readers more interested in specific topics regarding EOL applications, such as recycling, for example. Notably, many insights gathered during the interviews could be conflicting from one company to another, which indicates that the organizations have particular views, or different approaches, to solve the same problems. The difficulty in obtaining data on failure was also acknowledged and, with companies reluctant to disclose their errors, this can create a scenario that potentially leads others to repeat their mistakes. Which means that although this thesis included an investigation into challenges and future perspectives, further research could expand the knowledge on this topic.

The proposed design for a BRC intentionally centers on the single case study for Volvo Group. While single case studies are criticized for yielding context-specific insights, limiting the generalizability and applicability of findings (Eisenhardt & Graebner, 2007), the rationale behind this choice was outlined in section 2.1.2. On the other hand, during the exploration phase and data analysis for *RQ1* and *RQ2* the findings were extrapolated from patterns and themes observed across various cases and sources, guided by the theoretical concepts and analytical framework outlined in section 2.1.1. Therefore, many examples and similar scenarios were discussed throughout the study and may be of great value for both practitioners as well as academia and policymakers.

The last reflection lies in the analysis of documents and media reports from companies to describe the reverse logistics and processes related to the return of EVBs and their preparation for second life applications. It's important to acknowledge that information provided by these sources may be constrained by the perspective, bias, and agenda of the authors. In this thesis, the author operated under the assumption that company reports accurately portray their activities, aiming to gain a general understanding of EVBs second life strategies and BRC capabilities. As an example, there is the fact that many companies' reports or websites advertise the possibility for the application of a broad range of solutions for the second life EVBs. But the interviews uncovered that they were only focusing on some of them (e.g., recycling and repurposing, but not remanufacturing) or even not yet prepared to offer a solution for the reported option.

6 Conclusion

This chapter will conclude the thesis by summarizing the key findings, addressing the research objectives, and answering the research question. Then, the theoretical and practical contributions for practitioners, policymakers and future research will be discussed.

The current trend of moving towards an electrified vehicle fleet is leading the demand for these vehicles to rise and increase the expectations for the future. Hence, with the number of sales for LDEVs and HDEVs exponentially growing, the volume of batteries that will reach their EOL stage are naturally on the rise as well. This study intended to explore what would be an optimal framework for the return logistics flow of EVBs at the end of their first life, including the capabilities for a BRC. To do so, three research questions were posed and answered as follows:

RQ1: What model capabilities are necessary for a BRC from a supply chain perspective?

The findings indicate a series of connected capabilities that are the core for effectively returning EVBs from their first life and connecting them to their second life. Given the complexity of their relation, capabilities that have more general tasks and that will be applied to all batteries in the flow were classified as *basic capabilities*, namely Receiving, Inspection, Sorting, and Shipping. While the *advanced capabilities* will comprehend the more complex and technical activities of Pre-Diagnosis, Cleaning, Dismantling, Charging/Discharging, Testing, Storing, and Second life preparation.

RQ2: What are the best practices for the Reverse Logistics of EVBs at the end of their first life? How and why are companies performing in this way?

The industry investigation has shown that companies have different focus on their strategies for the second life of EVBs, with repurposing and recycling being the most prominent among the participants. Still, all companies indicated as planning for expanding towards an offering of all CE strategies. Additionally, the interviewed companies’ view for EVBs lifecycle and their long-term strategy are directly connected to goals of innovation and sustainability. However, the return logistics of the EVBs can greatly change from one company to another, both in terms of goals and processes. The results highlight, nevertheless, that the differences are not mutually exclusive for the operationalization flow. Which means that companies may plan and execute the processes under the BRC capabilities in different ways but aiming to solve the same problems. Moreover, the findings suggest that key factors can influence the design and construction of a framework for a BRC, both internally and externally to the organizations. Especially for the *Regulatory and Policy framework* playing a major role in the guidelines for creating the processes that make a BRC, and for the *Logistical Challenges* originating mainly from the lack of standardization and the week links to 3PLs in the supply chain.

RQ3: How should Volvo Group design its BRC reverse logistics in the EU?

The combination of the explored literature, regulations, industry, and internal discussions to Volvo Group, culminated in the creating of a design for a BRC that can be implemented in two different phases. Initially, the *Basic Capabilities* can be used in the short term as a way to organize the current processes that are being performed on individual level for each EVB in the return flow, while representing an opportunity to gather information and solidify the logistical processes. Later, the *Advanced Capabilities* can take place in a longer term to complete the BRC design and act as a complete solution for integrating the different steps in the EVBs’ lifecycle. That way, Volvo can have the flexibility to adapt along the way with the changes that may happen in the industry or to incorporate new findings. Moreover, the capabilities in this design take in consideration the scalability for an industry that are expected to grow on a very high rate in the near future.

6.1 Recommendations for practitioners

This thesis features the importance for creating a structured return flow for EVBs after the end of their first life and building up capabilities to prepare them for the second life journey. The establishment of a BRC hold significant potential from a CE standpoint and is crucial for the supply chain of EVBs lifecycle. As a result, it is advisable to practitioners that this entire flow should be supported by companies’ strategy and have a proper planning, rather than rely on a short-term perspective. The context calls for the designing of a BRC that is adapted to the needs of specific organizations, being flexible enough to address its logistical challenges and scalable enough to safeguard for the expected increase in volumes for second life EVBs. The implementation of the *basic capabilities* should be natural for companies used to the reverse logistics of the supply chain; however, the *advanced capabilities* require in-depth investigation and specific technologies for exploring their benefits. Lastly, it is worth mentioning that several of the “big” automotive companies in the industry are investigating similar problems as the ones presented in this thesis, and different solutions may arise and complement the results achieved here.

6.2 Recommendations for policymakers

EU policymakers would benefit from crafting a coherent regulatory framework that supports the sustainable development of CE strategies for EVBs while enhancing the economic viability of relevant capabilities that are inherent to the return flow in supply chain. This is crucial given the findings of this research, which underline clear environmental benefits, but shows that the industry is still lacking in the economic viability. Specifically, initiatives that expand the responsibilities on the flow to encompass OEMs and 3PLs. Furthermore, it is advisable to sustain and reinforce support for the development of a European EVB value chain to foster geographical proximity between European companies and organizations from other continents, which can be a mutual benefit for evolving the whole industry. Additionally, policymakers are encouraged to advocate for initiatives and research aimed at standardizing methods for the different capabilities in the return flow.

6.3 Recommendations for future research

Additional research is necessary to systematically evaluate and compare various processes that build up the capabilities that form a BRC. A more dynamic assessment, incorporating technological advancements when analyzing the alternatives for sorting, testing, charging/discharging, and dismantling the batteries, would be beneficial. Furthermore, future research should focus on analyzing and creating an optimal strategy that encompasses not only the internal capabilities of a BRC, but also the processes at dealers when collecting first life EVBs and at the other side of the flow, on the processes for transforming the battery in a new (or renewed) product. Moreover, there is a need to further investigate the economic aspects for reasonable profitability in the EVBs second life solutions and how the processes in a BRC can contribute for that goal. Lastly, future studies should explore the full spectrum of the activities inside each capability to understand the role of models, like gap exploiters in the system. It's crucial to investigate how standardization can be beneficial to improve the flow efficiency and on how the data gathered from several sources in the flow can be shared and transformed for a useful purpose.

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APPENDIX

A. Interview list

#	Company	Representative	Position	Date	Time (hh:mm)
1	Company A	Respondent 1	Project Manager	10/01/2024	00:45
2	Company B	Respondent 2	Technical Business Developer	23/01/2024	01:05
3	Company C	Respondent 3	Operations Manager	26/01/2024	00:50
4	Company D	Respondent 4	Supply Chain Specialist	02/02/224	00:55
5	Company E	Respondent 5	Project manager for electrification	09/02/2024	00:35
6	Company F	Respondent 6	Recycling Manager	19/02/2024	00:50

B. Interview guide

Block	Topic	Questions
1	Introduction	1. Could you please present the core business activities of your organization and your role in this organization? 2. How engaged is your organization in the circular business for automotive LIBs? (Return, Remanufacture, Repurpose, Recycle)?
2	Lifecycle and strategy	3. Could you please describe the current life cycle of LIBs within your organization? 4. What is your organization main goal in operating in the circular economy for LIBs?
3	Return cycle	5. How does your organization organize its reverse logistics of LIBs (describe the logistics flow)? 5.1 How does a customer return a LIB? 5.2 Are LIBs always transported in packs? Do you have a standard box/container? 6. Do you perform any kind of diagnosis on the battery prior to the collection from your suppliers? 6.1 Does your organization accept all LIB or is there a selection criteria? 6.2 Does the returned LIB already have a chosen destination (Repairing/Repurposing/Recycling) or are they tested before deciding?
4	Remanufacturing / Repurposing	7. Could you please describe your internal process flow? 7.1 **Sorting**: 7.1.1 Do you have separate flows for functional and failed LIBs? 7.1.2 Can you highlight the differences? 7.2 **Cleaning**: 7.2.1 Does it follow a given standard or is it a simple process that only aims to allow the operator to interact with the battery? 7.2.2 Do you use any special equipment? 7.3 **Charging / Discharging**: 7.3.1 Do you charge/discharge all batteries? 7.3.2 Are the batteries charged/discharged more than once during the whole process? 7.4 **Diagnosing / Testing**: 7.4.1 Do you perform a simple and quick test for identifying battery health or an in-depth examination to get all the internal details? 7.4.2 Do you perform diagnosis tests in all received LIBs? If not, how do you choose which are the ones that should be diagnosed? 7.4.3 Do you have a proprietary system for storing data and evaluating diagnostics? 7.5 **Storing**: 7.5.1 Do the batteries have a maximum storing time? 7.5.2 Do you control the inventory levels of temperature and humidity? 7.5.3 Do you follow any security standards or regulation for storing the batteries? 7.6 **Shipping**: 7.6.1 Do you perform any check on the batteries prior to shipping them? 7.6.2 Do you charge / discharge the batteries again prior to shipping them? 8. Do you have a clear bottleneck on your process? 9. What factors contribute to the success of your organization’s reverse logistics set-

		up? 9.1 Which strengths does your organization build on to successfully set up a reverse logistics system for LIBs? 10. What are the main challenges that remain for your organization to set up a reverse logistics system for LIBs?
5	Recycling	11. Does your organization collaborate with your cell/battery suppliers to have a closed-loop recycling? And if yes, how? 12. Is recycling LIBs a cost or a potential business case for your organization? 13. What factors contribute to the success of your organization’s LIBs recycling activities? 14. What are the main challenges that remain regarding recycling within your organization?
6	Future Scenario	15. If you operate in Europe, do you see that the new EU regulations will impact your organizations' operation? If yes, in what way? 16. How do you think the industry will develop in the next 5 / 10 / 15 years?