DESIGNING A SUSTAINABLE UK END-OF-LIFE REVERSE SUPPLY CHAIN FOR ELECTRIC VEHICLE BATTERIES

MELISSA LIZETH VENEGAS VALLEJOS

Doctor of Philosophy Business & Social Sciences

Aston University

March 2024

Designing a sustainable UK end-of-life reverse supply chain for electric vehicle batteries

Melissa Lizeth Venegas Vallejos

Doctor of Philosophy Business & Social Sciences, 2024

Thesis Abstract

Environmental, legal, social and economic concerns have recently prompted manufacturing organisations to implement more sustainable supply chain methods and create end-of-life (EoL) reverse supply chains (RSC). This research aims to explore the requirements to design a sustainable EoL RSC in an emerging sector. Additionally, it aims to develop a modelling tool that facilitates the EoL RSC design and assessment. This research uses a mixed-method case study approach and develops a discrete-event simulation tool to study the design of a sustainable EoL RSC. The study findings indicate that the inefficiency in the EoL processes and the uncertainty in the EoL market have a significant impact on the sustainability of a RSC for EV batteries. Hence, the implementation of regulatory frameworks and collaborative methods is imperative for emerging RSCs in order to enhance the efficiency of their operations. Furthermore, in order to create EoL solutions that are both environmentally friendly and economically feasible, it is imperative to conduct testing of these solutions in prospective markets. This study presents a simulation model that academics and practitioners can use to model an emerging EoL reverse supply chain and measure the effect of design changes in terms of operational, economic and environmental impact.

Keywords: Reverse Supply Chain Design, Simulation, Electric vehicle batteries

DEDICATION

To my parents, Tina and Lolo, who inspired a little Peruvian girl to dream big

Acknowledgement

This PhD research has been a challenging journey that has taught me so much, not only about academic research but also about my personal strengths. Finishing successfully this PhD would not have been possible without the support of so many people who believed in me and supported me throughout these years.

I would like to thank my supervisors, Dr Andrew Greasley and Dr Aristides Matopoulos, for their unwavering support. I also want to thank the Business School and the Dean Scholarship for supporting this research. I am also grateful to the participants of my research. Without their valuable input, the completion of this thesis would not have been possible. I would also like to thank all my friends and colleagues I met at Aston University, who shared their valuable time with me, cheered me up, and encouraged me to keep going. I want to thank my friend Annabelle especially.

Finally, I want to thank the most important people in my life: my family. I want to express my sincere gratitude to my husband, Dr Filipe Sarmento, for his love, kindness, and patience during these hectic years. I also want to thank my parents, Tina and Lolo, who made so many sacrifices and worked hard so that my siblings and I could get the best education. I would like to thank my siblings, Betty and Cheo, who have loved me, protected and guided me since I was little.

List of contents

List of figures

List of Tables

1. Introduction

1.1. Research Background

During the last decades, sustainability has become an important topic worldwide and a priority in academia and industry due to the growing concern about the effects of climate change on the environment and global warming. The development of reverse supply chains is aligned with this paradigm shift. In the past, supply chain processes were considered forward flows that only focused on supply, production, and distribution to end customers. However, in recent years, environmental, legal, social and economic factors have been encouraging manufacturing companies to adopt greener and more sustainable supply chain practices and are accounting for the end-of-life (EoL) of products (Kazemi, Modak and Govindan, 2019). Consequently, businesses are now looking at supply chains more broadly and considering the reverse flow, creating reverse supply chains. A Reverse supply chain consists of all the parties and processes involved in collecting products from a customer to recover value or dispose of them (Guide Jr. and Van Wassenhove, 2002).

Several authors have conducted empirical RSC studies focused on developed industries with mature RSCs (Lind, Olsson and Sundin, 2014; Flygansvaer, Dahlstrom and Nygaard, 2018). Mature supply chains are characterised by having stable demand levels, strong and reliable supply chain processes and supporting technologies (MacCarthy *et al.*, 2016). Emergent supply chains, in contrast to mature industries, have unpredictable supply and demand, undefined processes, developing technologies and a reduced number of supply chain actors (Sebastiao and Golicic, 2008; MacCarthy *et al.*, 2016). Hence, there was an opportunity to expand the RSC literature by conducting a study in an emerging RSC due to their particular challenges.

The automotive industry is experiencing significant challenges in its reverse supply chain in the coming years due to the rapid growth of electric vehicle (EV) adoption. According to the latest Global EV Outlook Report (International Environmental Agency, 2024), around 14 million electric cars were sold in 2023, representing a 35% increase over the previous year. The report suggests that in Europe, in particular, new electric vehicle registrations approached 3.2 million in 2023, an increase of over 20% compared to 2022. The sales trends of electric vehicles in Europe indicate that growth continues to be strong as markets evolve. As the Goldman Sachs report suggests (2024) electric vehicle batteries are the most critical component of electric vehicles. Even though batteries have become less expensive over the years, the report suggests that they account for one-third of the total vehicle's cost and are highly relevant for EV development and adoption.

A study from Etxandi-Santolaya (2024) suggests that EV batteries typically last 10 years. Therefore, if the EV sales trend continues to grow steadily, as suggested by the IEA (2024) report, the EoL supply chain of this component needs to be prepared to handle the increasing volumes of batteries that are going to reach their end-of-life in the following decades. Electric vehicle batteries require unique management when reaching their EoL for several reasons. Firstly, the EV battery industry may face a shortage or rise in the price of some of the critical raw materials used in battery production (International Energy Agency, 2018; Moores, 2018). Therefore, recovering EV battery materials could help save costs and preserve raw materials. Secondly, according to the latest BloombergNEF Electric Vehicle Outlook (2024), lithium-ion chemistry is used in two-thirds of electric vehicle batteries. Lithium-ion batteries use metals such as lithium, cobalt, nickel, and graphite that may harm the environment and human health if not disposed of properly (Winslow, Laux and Townsend, 2018; International Energy Agency, 2019). Therefore, the EoL management of batteries contributes to the reduction of the EV carbon footprint. Thirdly, several human safety hazard risks are associated with battery handling, and it is necessary to follow careful procedures to minimise the risks (Zeng, Li and Liu, 2015). Therefore, assigning this work to professional OEMs (Original Equipment Manufacturers) and third-party logistics 3PL providers is essential. Lastly, under the latest Regulation (EU) 2023/1542 *"European Parliament and of the Council concerning batteries and waste batteries"* that was released in July 2023 (European Commission, 2023), EV manufacturers are responsible for the environmental impacts of the batteries used in their vehicles right up until the end-of-life cycle.PwC Electric Vehicle Sales Review (2023) suggests that the UK is among the five biggest EV European markets, and the British government has been showing the support to the automotive sector's electrification in several ways. The UK and the European Union (EU) have agreed to extend their tariff-free trade in electric vehicles, potentially saving car manufacturers and consumers up to £4.3 billion in additional costs (GOV.UK, 2023b). Moreover, the UK government has been attracting investment in EV battery gigafactories and EV manufacturing. Nissan is investing £3 billion to develop EVS in Sunderland. At the same time, BMW is investing £600 million to build Mini EVs in Oxford (GOV.UK, 2023a). Envision and Tata are investing £450 million and £4 billion in new gigafactories (AESC, 2023; GOV.UK, 2023c).

Despite all the important investments in EV and EV battery manufacturing, the UK end-of-life electric vehicle supply chain is at a developing stage. The number of EVs (electric vehicles) and EV batteries reaching their end-of-life is still low, and several EV manufacturers have not yet defined the structure of their EoL reverse supply chains.

1.2. Research problems and gaps

RSC (Reverse supply chain) is defined as the group of activities performed to recover products that customers no longer use and reprocess them to recover part of their value or for disposal (Guide Jr. and Van Wassenhove, 2002; Gupta, 2012). As Carter and Ellram (1998) suggest, the reverse supply chain is a relevant topic for academics and practitioners because it adds value to supply chains and makes them more sustainable. The interest in the RSC topic can be evidenced in the over 800 academic publications released in the past decades in the top 20 journals, as indicated in the bibliometric analysis by Kazemi et al. (2019)

According to MacCarthy *et al.*, (2016) supply chains like products pass through different stages (i.e. Emergence, growth maturity and decline). Most of the RSC studies focused on developed industries with mature RSCs, such as electronics, automotive, metal scrap, packaging materials, paper and apparel (Lind, Olsson and Sundin, 2014; Flygansvaer, Dahlstrom and Nygaard, 2018). While mature supply chains have stable demand, strong and reliable supply chain processes and supporting technologies (MacCarthy *et al.*, 2016), emergent supply chains have unpredictable supply and demand, undefined processes, changing technologies and limited supply chain actors (Sebastiao and Golicic, 2008; MacCarthy *et al.*, 2016). Therefore, there is an opportunity to contribute to the RSC literature by conducting a study in an emerging RSC to gain new insights.

According to Kazemi, Modak and Govindan (2019), the most researched study subjects within the reverse logistics and reverse supply chain literature are network design and planning (Jayant, Gupta and Garg, 2014; Jindal and Sangwan, 2014), followed by survey (Dowlatshahi, 2010; Abraham, 2011) and price and coordination (Chen and Chang, 2012; Zhao, Liu and Wei, 2013). Several authors have addressed the topic of reverse supply chain design by developing models. Five interesting models were found in the literature (see, for example, Jindal & Sangwan, 2014; Ghorbani et al., 2014; Das & Dutta, 2015; Jayant et al., 2014; Yanikara & Kuhl, 2015). Three out of the five papers reviewed used complex mathematical model approaches (e.g. linear and non-linear programming) (see, for example, Jindal & Sangwan, 2014; Ghorbani et al., 2014; Das & Dutta, 2015) to suggest alternatives to improve the efficiency of the processes rather than to achieve supply chain sustainability. A significant limitation of these modelling approaches is the limited flexibility and difficulty for non-experts in mathematical modelling to build these models and adapt them to reflect industry cases. There is also a lack of industry case studies; 80% the papers found in the literature present illustrative cases with created data.

Some practical simulation models were found in the literature (see Jayant et al., 2014; Yanikara & Kuhl, 2015); however, within the models reviewed, they were limited to a quantitative analysis without a thoughtful understanding of the industry context and other factors that influence design decisions such as industry stage, suppliers' resources and capabilities or legislations. The models studied mainly include manufacturers and recyclers in their reverse supply chain models. The models found in the literature do not consider other key stakeholders such as remanufacturers, refurbishing companies and second-life repurposing companies. The relevance of building appropriate relationships between them to build successful and sustainable supply chains is also overlooked.

The literature about the modelling approaches used in supply chain research is also reviewed. The main types of simulation modelling techniques (i.e. system dynamics, DES) were identified, and the operational research (OR) intervention approaches (i.e. expert mode and facilitated mode) were discussed. Several applications of modelling techniques are identified in the literature. Most of the modelling case studies have used the expert mode intervention approach. As Robinson et al. (2014) suggest, the purpose of a facilitative simulation modelling is to develop an understanding of a specific topic and promote discussion by using the simulation model as a supporting tool. Facilitated modelling is a useful intervention approach to studying and analysing complex problems to make strategic-level decisions, especially in cases where there is a lack of historical or appropriate data to do an objective analysis using simulation. This research looks to study and model a supply chain that does not exist and is still developing. For this reason, the facilitated modelling approach was identified as a suitable strategy.

Moreover, it was identified that there is a lack of theory use in the literature related to this study. Most of the papers that address the topic of sustainable supply chain and reverse supply chain are a-theoretical. Seven academic papers were found that used well-established theories to study concepts and relationships to contribute to academic knowledge (e.g. Ashby, 2018; Kalaitzi et al., 2019; Madadi et al., 2013; Masoumik et al., 2014; Aristides Matopoulos et al., 2015; Miemczyk et al., 2016; Wong et al., 2012). One of the theories used in the sustainable and reverse supply chain context is the Natural Resource-Based view (NRBV). The NRBV suggests that a firm can obtain a competitive advantage by recognising the challenges imposed by their organisation's natural and social environment and developing business capabilities to react to them (Hart, 1995). The NRBV involves the development of internal capabilities but also considers stakeholder and institutional considerations as external aspects of the strategy (Hart, 1995). Some authors have made significant contributions to the knowledge by developing frameworks for sustainable supply chain design (SSCD) (Masoumik *et al.*, 2014); studying the strategic resources needed to develop successfully closed-loop supply chains (Miemczyk, Howard and Johnsen, 2016); and investigating how CLSC can be successfully developed to address sustainability (Ashby, 2018). For this reason, the NRBV theory was chosen to guide this research and to identify the necessary elements to design a sustainable reverse supply chain.

A summary of the main research gaps identified in the literature review and theoretical papers discussed above are presented in Table 1.1

Table 1.1. Summary of Research gaps (Author,2024)

N°	Research gap	Addressed in this study
1	The supply chain modelling case studies found in the literature collect historical data on processes using the expert mode intervention approach.	Using a facilitated modelling approach, model a supply chain that is still developing and does not exist with limited historical data.
2	Previous research on RSC design has been limited to the use of complex mathematical models that are complicated for non-experts to build and adapt to reflect real industry contexts. Only two of the models focus on sustainability, and there are limited industry cases.	This research uses a mix-methods approach that will combine qualitative and quantitative methods. A facilitative simulation modelling process in an industry context was chosen to allow the stakeholders to understand the problem situation better and assess potential improvement alternatives to make their RSC more sustainable.
N°	**Research gap**	**Addressed in this study**
3	The practical models found in the literature ignore the industry context and other factors that influence design decisions.	Through the mix-methods approach, this research considers the impact of the industry context (i.e. Drivers and barriers for implementing environmental strategies, EoL Reverse supply chain elements and Sustainable Reverse supply chain strategies)

4	The models studied include only manufacturers and recyclers, ignoring other key stakeholders and their relationships.	This research will include the main actors in a reverse supply chain, such as recyclers, remanufacturers, refurbishing companies and second-life repurposing companies, and the relationships between them to build successful and sustainable supply chains.
5	Lack of theory used in the literature related to reverse supply chains	The use of NRBV theory will guide this research and identify the necessary elements to design a sustainable reverse supply chain.

1.3. Research aim, question, and objectives

This research explores how to design a sustainable EoL reverse supply chain in an emerging sector.

To bridge the gaps identified in the literature, the research questions guiding this research are the following:

- ***RQ1:*** *What are the requirements for designing a sustainable EoL RSC in an emerging sector?*
- ***RQ2:*** *How can an EoL RSC be designed to meet operational and sustainability objectives?*

The study objectives of this research are the following:

I. To identify the requirements to design a sustainable EoL RSC.
II. To develop a framework that can support identifying requirements to design a sustainable EoL RSC.
III. To develop a modelling tool to support the EoL RSC design and assessment of operational, economic and environmental sustainability objectives.

1.4. Research design and thesis structure

Even though the volume of batteries reaching their end-of-life is still low, there is an increasing demand for electric vehicles.If the EV sales trend continues to rise gradually, as projected by the IEA (2024) research, the EoL supply chain of this component must be prepared to accommodate the increasing volumes of batteries that will approach end-of-life in the coming decades.. There is a need to minimise the batteries' raw material extraction and decrease the environmental impact of electric vehicle batteries (Moores, 2018; Winslow, Laux and Townsend, 2018; International Energy Agency, 2019). Moreover, regulations are continuously revised to forbid the disposal of electric vehicle batteries without previous treatment (European Commission, 2023).

To achieve the study objectives, a literature review on reverse supply chain design is conducted to identify the main research gaps. In this research, the NRBV theory was chosen to guide this study and identify the necessary requirements to design a sustainable reverse supply chain. The natural NRBV theory was also used to support the development of this study's conceptual framework. The proposed general framework of this study is based on three main constructs: Drivers and barriers to implementing environmental strategies, EoL Reverse supply chain design and Sustainable Reverse supply chain.

A mixed-methods approach that combines qualitative and quantitative methods was chosen. This research follows a sequential process with two phases. In the first phase, qualitative data is collected from interviews with managers and directors of a remanufacturing company, a material recycling company, a scrap recycling company that has a national Authorised Treatment Facility (ATF) network, and a company that has been using EV battery cells for second-life applications. The interviews aim to understand the current situation of the UK EoL electric vehicle battery supply chain and the main drivers and barriers to reverse supply chain implementation. The interview insights are also used to understand the main EoL processes, the role of the main RSC stakeholders, and future sustainability strategies. The final phase of the mixed-methods involves collecting quantitative and qualitative data through interviews and questionnaires and a facilitated intervention to a group of supply chain managers engaged in the electric vehicle battery industry. A facilitative Discrete-event simulation modelling technique is used to understand the complexities of the EoL reverse supply chain, foment discussion and assess different sustainable configurations. A summary of the thesis structure of this study is presented in Table 1.2.

Table 1.2. Thesis structure (Author, 2024)

Chapter	Description

Chapter 1 - Introduction	An introduction to the research background, topic, and problems are presented. The aim of the study, research questions and objectives are outlined.
Chapter 2 - Literature review	A literature review is conducted, and the main approaches used in reverse supply chain design studies are discussed. The research gaps are identified, and the research questions are formulated.
Chapter 3 - Theoretical Perspective	The most important theories used in the sustainable supply chain management and reverse supply chain domain were analysed, and NRBV was selected as the theoretical lens for this research.
Chapter 4 - Conceptual Framework	A conceptual framework is developed and used to structure and guide this research.
Chapter 5 - Research design	The research philosophy, approach and strategy are explained, and their selection is justified.
Chapter 6 – Findings from case studies	The industry case study is conducted and analysed.
Chapter 7 - Findings and discussion from the cross-case study analysis	Cross-case analysis findings, revised framework and propositions
Chapter 8 - Simulation study analysis and discussion	A simulation study is developed. The process followed to conduct the simulation study is explained, and the main results are discussed.
Chapter 9 - Conclusions	The conclusions, theoretical and practical contributions, limitations, and future research opportunities are described.

2. Literature review

2.1. Overview

In this chapter, an overview of the literature review is presented. Section 2.2 Sustainable supply chainsdiscusses the literature related to the triple bottom line of sustainable supply chains and the impact of supply chain decisions on resource use. The second section focuses on Supply chain modelling, the main types of simulation modelling used in SC research, and the expert and facilitated mode of operational research intervention. The third section starts by reviewing the main RSC definitions and research categories. Then, the main approaches used in RSC design are discussed. The fourth section analyses the business relationships in previous RSC research work. The fifth and sixth sections focus on the context of the EV sector and the challenges of the electric vehicle battery industry. In the last section, the research gaps are identified, and the research questions are formulated using the insights of the literature review.

2.2. Sustainable supply chains

2.2.1. The "Triple bottom line" and the supply chain

During the last decades, sustainability has been on the agenda of academics and practitioners due to the growing concern about the environment, global warming, and climate change. In 1987, United Nations' World Commission for Environment and Development, chaired by former Norwegian Prime Minister Gro Harlem Brundtland, defined sustainable development as *"the development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (Brundtland, 1987).

Sustainability is also linked to corporate social responsibility (CSR). A socially responsible company should minimize its environmental impact, look after its employees, and have good relationships with clients, suppliers, and stakeholders (Grant, Trautrims and Wong, 2017). Companies that aim to be sustainable and continue being profitable in the long term should pay attention to the impact of their activities beyond the firm boundaries (Christopher, 2016).

In 1994, Elkington (1994) aimed to create a concept beyond sustainable development and CSR. As Elkington (1994) suggests, companies seeking to be sustainable should not measure their success only in terms of the financial bottom line but also consider the concept of *"triple bottom line"* (TBL) in their assessment. Elkington (1994) developed the TBL framework to change the mindset of companies doing business, emphasizing economic success, social development, and environmental value. According to Elkington (1994), sustainability consists of three pillars: social, economic, and environmental.

These pillars constitute the TBL or, as some authors prefer to call, the 3 Ps, People (society), profit (economic) and planet (environment) (See Figure 1.1). The TBL highlights the relevance of assessing the effect of a firm's decisions on three areas. According to Christopher (2016) , Belvedere and Grando (2017) the environmental , economy and society areas are described as follows

- Environment (Planet): environmental sustainability refers to the impact and protection of the environment (e.g. pollution, global warming, resource efficiency)
- Economical: the performance that generates sustainable positive financial results for an extended period (e.g. company's financial results, financial security of people).
- Society: social implications of the company and protection of human rights (e.g. poverty reduction, employees working conditions, people's living conditions).

The TBL concept suggests that companies should maximise shareholder value while adding environmental and social value to continue operating in a safe, natural environment in the long term, ensuring good living conditions for humans. The TBL has been widely accepted by industry organisations and governmental and non-governmental institutions (Grant, Trautrims and Wong, 2017) (Belvedere and Grando, 2017).

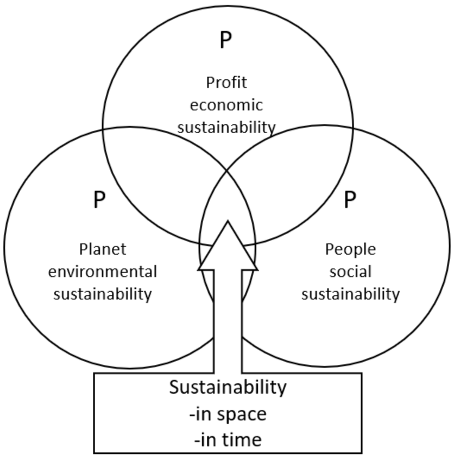


Figure 2.1. 3Ps and the Triple bottom line (Belvedere and Grando, 2017)

The concept of TBL has also translated to the supply chain context. As Chopra (2019) suggests, even though each supply chain represents a small part of the world where it belongs, the subsistence of supply chains and habitats depends on the health of the world where it operates. Consequently, sustainability pressures are also affecting supply chains. The sustainable supply chain has become an important topic between academics and practitioners. Supply chains have been experiencing more governmental, environmental and social pressures than ever before (Morana, 2013). The aim of a supply chain should go beyond the particular interest of a supply chain actor; instead, supply chain decisions should consider other stakeholders outside the supply chain and how they may be affected (Chopra, 2019). Govindan, Paam and Abtahi (2016) and Joshi (2022) argue that sustainable supply chains should work to provide advantages towards the three pillars of sustainability: environmental, economic and social. The triple bottom line elements are highly interrelated and support each other also in the supply chain context. Supply chain strategies that positively impact the environment will, in most cases, generate savings for the companies in the long term due to a more thoughtful use of resources (Christopher, 2016). As supply chain decisions significantly impact the efficiency and efficacy of operations, it is worth analysing the different supply chain processes to look for opportunities to improve sustainability. Moreover, as Christopher (2016) suggests, companies must consider the sustainability impact on the whole product lifecycle, from product design to end-of-life management. For this reason, the development of reverse supply chains is an essential contributor to sustainable development.

2.2.2. Impact of supply chain decisions on the resource footprint

New environmental restrictions limit carbon emissions in supply chains (Kabadurmus and Erdogan, 2020) Several international organizations have highlighted their fears about the future availability of natural resources and the possible consequences for several industries (OECD, 2019; BCG, 2021). Even though sustainability has been on the agenda of supply chain management research and practice, the relationship between supply chains and natural resources has been overlooked (Hart and Dowell, 2011).

For that reason, as Christopher (2016) suggests, supply chain decision-makers should focus not only on reducing their operations' greenhouse emissions but also on how scarce resources are used across the five areas of the supply chain (design, source, make, deliver, return). Figure 2.2. shows how the decisions made at each value chain stage affect the resources' footprint. As several natural resources are becoming scarce rapidly, firms must understand the influence of the supply chain decisions on resource usage at each stage of the value chain.

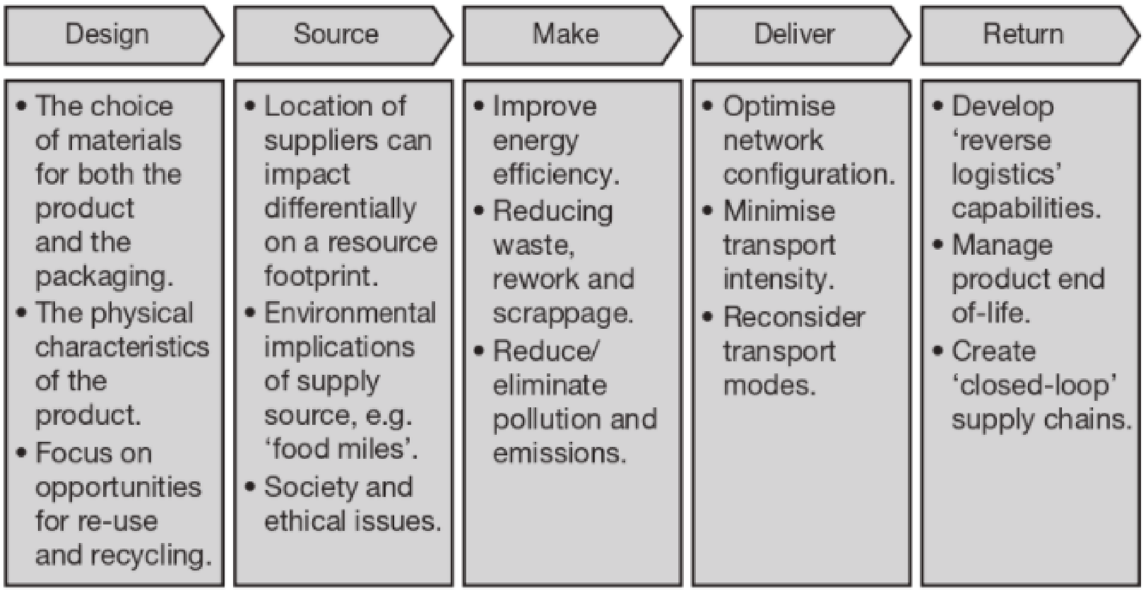


Figure 2.2. The supply chain decisions impact on the resource footprint (Christopher, 2016)

Design

The decisions made in the product design stage significantly impact the product market success and the sourcing, production, distribution and supply chain performance in general (Christopher and Peck, 2002). Christopher and Peck (2002) book shows some example of companies, trying to reduce the amount of packaging material used in their products. While, other companies are opting for other, less straightforward alternatives to improve the use of resources. If the people responsible for new product development do not consider the repercussions of the design decisions on the natural resources, this could cause the introduction of a product to the market with a higher resource footprint than initially thought (Christopher, 2016). An example of the resource implications of supply chain decisions is the high-technology products that depend on rare earth metals, whose availability may reduce significantly in the following years (Christopher, 2016).

Source

Within the sustainable supply chain management field, 'sustainable sourcing' has emerged as a relevant research and management topic (Walker *et al.*, 2012; Zimmer, Fröhling and Schultmann, 2016; Akhavan and Beckmann, 2017). Procurement plays a vital role in sustainability, and sustainable sourcing has already become an essential element of best-practice procurement (Seitz and Wells, 2006). To be sustainable, a supply chain cannot ignore its upstream operations. According to Christopher (2016), about 50% of manufacturers' carbon footprint is produced upstream of their operations. Hence, the way materials and products upstream are made and sourced can significantly impact resource consumption. For instance, companies looking to reduce the upstream environmental impact could work with suppliers to reduce the toxicity of the sourced materials or the packaging used to store and transport supplies (Sharfman, Shaft and Anex, 2009).

Make

According to the U.S. Department of Commerce report, sustainable manufacturing is defined as *"the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, and safe for employees, communities, and consumers and are economically sound"* (USDOC, 2012). As Christopher (2016) suggests, some of the ways manufacturing affects the resource footprint are energy use, the efficiency of operations, and disposal and management of effluents. Even producing the same product in different facilities could imply significant differences in energy use, waste generation and mode of disposal (Christopher, 2016). Another subtle aspect that could affect the resource footprint of operations is the energy source. The UK carbon trust did a study to compare the carbon footprint of a UK daily newspaper when using Swedish and UK newsprint (Christopher, 2016). In the UK, the energy production relies on coal and gas. Whereas in Sweden, the energy comes from renewable sources. For this reason, Sweden was the most sustainable manufacturing option (Christopher, 2016).

Deliver

Transportation decisions can have a significant impact on the environment. Transport can significantly affect the carbon footprint of supply chains since they depend heavily on oil resources. Moreover, as Waters and Rinsler (2014) suggest, transport emissions are considered part of the companies' carbon dioxide burden. In Europe and the UK, transport represented 29% and 27% of the total CO_2 emissions, respectively (European Parliament, 2020; Department for transport, 2021). In the case of the UK, in particular, more than 90% of the emissions corresponded to road transport, while Heavy Goods Vehicles (HGVs) accounted for 18% of road transport emissions (Department for transport, 2021). Another aspect that affects the transport CO_2 emissions is transport efficiency. Transport efficiency is dependent on the degree to which the vehicle's capacity can be maximised and used in both directions (Mason and Lalwani, 2006; McKinnon and Ge, 2006). According to a report presented by the European Commission DG for Mobility and Transport (2017), around 26% of the national road freight journeys in the EU were empty runs. In the UK, 29% of the domestic road freight vehicles kilometres were run empty (Department for Transport, 2019). According to the

Department of transport (2017), empty running costs the freight industry £160 million only in fuel a year and generates 426,000 tonnes of Greenhouse Gas (GHG) emissions. Also, the delivery network configuration can significantly impact supply chain sustainability. As Christopher (2016) suggests, several companies have used optimization tools to determine the best configuration network; however, most of the models arelimited to minimising the transport operations' costs and have overlooked the resource footprint.

Return

Reverse Logistics (RL) is "*the process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal*" (Rogers and Tibben-lembke, 1999, p.2). In the past, reverse logistic operations and their impact were overlooked; however, during the last decades, legal, environmental and social pressures have made firms pay more attention to the carbon footprint of the reverse logistic processes (Christopher, 2016). Nowadays, companies are trying to develop reverse supply chains to close the loop of their supply chains and increase the product value recovery at their end-of-life. As Christopher (2016) suggests, products should be designed considering their end-of-life impact, but the reverse supply chain network has to use as few resources as possible. Implementing reverse supply chains allows firms to reduce costs and, at the same time, reduce the carbon footprint of their operations.

2.3. Supply chain modelling

2.3.1. Modelling definition and model types

Modelling may be defined as a simplified representation of a system, usually through mathematical equations or graphics, to facilitate an understanding of the system's current situation and make the decision-making process easier (Matopoulos, Bell and Aktas, 2016). According to the purpose of the model, these could be categorised into three types: descriptive, predictive, and prescriptive (Matopoulos, Bell and Aktas, 2016). Descriptive models provide insights about what happened or is happening in a system and are generally used to represent the base case from which the improvements are suggested. On the other hand, predictive models are used to understand what could happen in the future, given what is known about a system. In contrast, prescriptive models aim to identify what should be done to reach a desirable outcome (Matopoulos, Bell and Aktas, 2016).

According to Greasley (2004), mathematical models can also be classified according to their nature as static or dynamic. Static models include linear programming, integer programming, and multi-objective mathematical programming used for optimization purposes. Static models are prescriptive models used to identify the actions needed to achieve a goal (e.g. profit maximisation, cost minimisation). Another static numerical method is the Monte Carlo method, which uses random variables to model risk and correspondent outcomes (Greasley, 2004). In contrast to static models, dynamic models represent changes in the system attribute as a function of time. Simulation models belong to the dynamic category of mathematical models and may be used for descriptive, predictive and prescriptive purposes (Greasley, 2019). Dynamic Simulation models are helpful to represent the variability and complexity of real systems. Dynamic models can be classified as continuous and discrete. Continuous models are generally used at a high level of abstraction (e.g. the cause and effect of an organizational system). On the other hand, discrete systems only change at discrete points in time (e.g. modelling operational manufacturing or services systems). The system dynamics approach is an example of a continuous dynamic model, while Discrete-event simulation follows the discrete dynamic mathematical modelling approach.

2.3.2. The relevance of modelling in SC research

The problems identified in the industry context are usually complex and require representative models to understand them better. Models are commonly used to identify points to be improved in a system to make the corresponding changes or predict systems' future behaviour. Models are useful for formulating a problem and developing solutions without trial-and-error tests that are impractical and costly. However, as Matopoulos, Bell and Aktas (2016) suggest, models that are not built with practical insights may not have explanatory power. Models are more useful when they represent a real situation; therefore, empirical data collection and analysis methods make them more powerful. Authors like Sanders and Wagner (2011); Sanders, Zacharia and Fugate (2013) and Choi, Cheng and Zhao (2016) have highlighted the benefits of combining analytical and empirical methods in multi-method approaches and how they can be applied in supply chain research A wide range of models has been used in the supply chain context (Lima-Junior and Carpinetti, 2017). They have proved to be a versatile tool to help the decision-making process in different industries and their correspondent supply chains. According to Matopoulos, Bell and Aktas (2016), empirically informed analytical models could provide significant contributions to knowledge. For instance, case studies and surveys may provide important insights from the current industry or business situation and be used to improve the design for more accurate analytical models. As Simchi-Levi (2014) and Sodhi and Tang (2014) suggest, since the parameters used in these models come from real industry contexts, they are more valid and generalizable to practice.

2.3.3. Simulation modelling advantages in SC management

According to Robinson (2014), simulation is one of the many methods to analyse and improve system operations, and it has been widely used due to its numerous advantages. Simulations are less costly than experiments with a real system because the alteration of a real system can cause a decrease in productivity or customer satisfaction (Robinson, 2014). Furthermore, the real system may not even exist in some cases, so it would be costly and impractical to build different real-world systems to evaluate them. Moreover, experiments in the real system may be time-consuming and usually require weeks or months to see results. Another advantage of simulation compared to experiments with the real system is the possibility of controlling the experimental conditions. In a simulation environment, the experimental conditions can be easily modified and repeated as many times as possible (Robinson, 2014). Simulations also offer multiple advantages compared to other modelling approaches. Simulations, as well as other static mathematical model approaches, can model variability. However, static modelling approaches that account for the variability are usually complex to build, and sometimes variability is not represented accurately. In contrast, simulations can represent variability with a high level of detail (Robinson, 2014). Static mathematical models may also have restrictive assumptions, such as specific distributions for certain processes, while simulations can use any distribution type. Robinson (2014) suggests that another key strength of simulation that static modelling approaches lack is transparency making it difficult for an industry manager to understand mathematical equations or believe their results.

In contrast, simulations are more transparent and intuitive and may give managers more confidence in the model results (Robinson, 2014). From a management perspective, simulations offer important benefits for managers. For instance, simulation promotes creativity since the simulated environment allows several experiments without risk. Robinson (2014) also suggests that stimulation may act as a catalyst to create knowledge and understanding. To build a simulation model, it is necessary to look for data and question assumptions leading to a better understanding of the system under study. Visual simulations are also useful for communication purposes and to convince managers of the validity of a proposed solution (Robinson, 2014).

2.3.4. Simulation modelling types in SC research

Simulation has been widely used as a problem-solving tool to address different RL and CLSC problems such as network design, facility location, capacity planning and system configuration as shown in papers published by Hai-jun *et al.*, (2007); Vlachos, Georgiadis and Iakovou (2007); Georgiadis and Besiou(2008); Yanikara and Kuhl, (2015); Chen *et al.*(2018). In addition, according to Abid, Hadji and Mhada (2019), the main techniques used to solve RSC and CLSC problems have been System dynamic (SD) and Discrete Event Simulation (DES).

System Dynamics

System Dynamics (SD) is a continuous model type where stocks of variables are connected via flows. Stocks represent accumulations of a resource (e.g. materials, people, money), and the flows represent the levels of these stocks (Greasley, 2019). The inflows raise the stock levels, and the outflows reduce them (Robinson, 2014). The stock change constantly in response to the inflows and outflows; therefore, SD models time continuously. SD can be used for multiple purposes, such as modelling supply chains. Some authors have studied the main similarities and differences between SD and DES and have concluded in general that SD is not appropriate when the system requires to be modelled in detail, especially when it is necessary to track individual items in a system (Tako and Robinson, 2010). For those cases in which modelling in detail and tracking of individuals in the system is needed, DES modelling could be more appropriate (Robinson, 2014).

Discrete-event simulation

Discrete-event simulation (DES) takes a process view modelling approach. DES is used to model systems with individual entities whose behaviour can be represented by a series of events that may change the system's state (Greasley, 2019). In a DES, the entities may have attributes or characteristics (e.g. age, product type). These entities move from one resource (e.g. machine, equipment and person) to another and consume work from the resources. A DES model can represent the number of resources and time available. When entities move from one resource to the next one, they can be immediately processed or wait in queues. Queues are created when some entities arrive at a faster rate than they can be processed (Robinson, 2014). DES allows many objects to be manipulated at the same time since it allows one to manage multiple events at a single point in time (Greasley, 2004). According to Banks *et al.* (2010), DES is the most famous Operational Research (OR) simulation technique. As shown in Jahangirian *et al.* (2010) systematic literature review focused on the use of simulation in manufacturing industries, DES is the OR technique that has been used the most in practical applications.

2.3.5. Modes of engagement in Operational research interventions

Operational Research (OR) models have proved to be a successful tool to address complex organisational problems. The *"expert mode"* has been the most common and widely accepted way to apply operational research techniques in organisations. In the expert mode, the operational researcher uses OR methods and models to objectively analyse the problem chosen to provide an optimal or close optimal solution (Franco and Montibeller, 2010). However, during the last decades, a new way to conduct OR in organisations has been developed which is called the "facilitated mode". In this new type of intervention, the operational researcher stops acting only as an analyst and adopts a facilitator role (Franco and Montibeller, 2010).

The expert mode in OR interventions

The "expert mode" is the conventional intervention mode used by operational researchers. In the expert intervention mode, the operational researcher is not only an OR expert but also an expert in the problem-related field. The operational researcher in the expert mode uses OR methods and models to analyse a specific problem objectively, find the optimal or close to optimal solutions to the client, provide recommendations on how to solve the given problem and the correspondent steps to follow for the implementation (Robinson *et al.*, 2014).. The expert mode has been used to solve a wide range of strategic decision problems in operations, logistics, marketing and finance (Franco and Montibeller, 2010). Table 2.1 shows the general steps that operational researchers follow in an expert-mode intervention and a facilitated mode intervention.

Table 2.1. Expert versus facilitated modes of OR consultancy (Franco and Montibeller, 2010)

	Expert mode	Facilitated mode
Framing problems	Problems are a real entity, thus the main task of the operational researcher is to represent the real problem that the client organisation is dealing with, avoiding “biases” from different perspectives.	Problems are socially constructed, thus the operational researcher has to help a management team drawn from the client organisation in negotiating a problem definition that can accommodate their different perspectives.
Formulating problems	The real problem has to be formulated as precisely as possible. It is the task of the operational researcher to formulate the problem.	The problem has to be structured by the managent team, whose members are aware about its different aspects and contextual details. The process of problem structuring is supported by the operational researcher, acting as a facilitator, and the development of a model that captures the structure of the problem.
Defining metrics	The expert defines the metrics to assess the performance of options, based mainly on the nature of the problem that the consultant is analysing.	The metrics to assess the performance of options reflect the objectives and priorities of the organisation, as defined by the managent team, and with the support of the operational researcher.
Collecting data	Data collection is always extensive and of a quantitative nature. It is the operational researcher that defines, based on the nature of the problem, what information has to be gathered.	Data collection may be extensive, depending on the problem, but involves not only quantitative but also qualitative data and preference information. The objectives and priorities established by the managent team guide which information will be gathered.
Evaluating options	The model is solved by the operational researcher, and optimal solutions for the problem are found.	The evaluation of options is conducted interactively with the managent team. The consequences of adopting each option are assessed by a model and this informs the team's discussions.
Presenting results	The optimal solutions are then reported back to the client, usually via a detailed report. It is crucial that the report makes explicit all the assumptions made, as the client was not involved in formulating the problem.	Results are shown interactively to the managent team. They are allowed “to play” with the model and see the consequences of implementing potential options. The report has typically a less important role, as it is the support for the decision making process that is the key for the client.
Committing for action	The operational researcher hopes that, given the scientific nature of the analysis, the client will be committed to implement its prescriptions.	The operational researcher hopes that the participatory process of reaching a decision, using a facilitated modelling approach, will increase the team's commitment to the implementation of the chosen options.
Paying the consultant	The client pays for the analysis, the prescription of solutions, and the operational research expertise about the problem.	The client pays for the decision support, the recommendations of actions, and the operational researcher's expertise on facilitating the decision making process.
Aim of the intervention	Provide the optimal solutions to the client.	Help the client in learning more about their problem and in gaining confidence for the way forward.

Franco and Montibeller (2010) also discussed some of the assumptions related to the expert mode in OR. The first assumption suggests that problems are real entities and do not depend on who describes them. Operational researchers should remove any bias when describing the problem to identify and solve it (Roy, 1993; Landry, 1995). The role of the OR expert is to structure a problem in the most accurate way and develop a detailed model without the client's involvement.

In most cases requiring an expert mode intervention, the data collected to build up the model is quantitative. The model in the expert mode is solved individually because of the technicalities used to solve the model. The third assumption suggests that clients expect the OR experts to provide a detailed report with optimal solutions and recommendations (Williams, 2008). The last assumption suggests that the analysis's implementation is straightforward. The implementation of solutions suggested by a well-performed OR analysis should not be complicated since the solutions are optimal according to the metrics used (Eden, 1982). The expert mode has proved to be an excellent technique to deal with management problems. However, according to Franco and Montibeller (2010), some of the reasons why the expert mode may not be adequate could be having an unclear problem scope, different stakeholders' priorities that need to be negotiated, and the participation level in the decision-making process.

The facilitated mode in OR interventions

Approximately forty years ago, a new way to conduct OR called *"facilitated mode"* was proposed, where the operational researcher stopped acting only as an analyst and adopted a facilitator role (Franco and Montibeller, 2010). This new way of conducting OR uses facilitated modelling as an intervention tool that demands the OR facilitator to conduct an intervention working hand-in-hand with the client. With the client's support, the facilitator can do important activities such as outlining the problem to be studied, creating the models, identifying the client's priorities, and giving recommendations for successful implementation (Franco and Montibeller, 2010). According to Franco and Montibeller (2010),the facilitated mode of intervention has proved to be a suitable strategy for analysing complex problems or making strategic decisions. The facilitated mode often involves the use of soft methods, Problem Structured Methods (PSM) (Smith and Shaw, 2019) or strategic development and analysis (Ackermann and Eden, 2020). In the facilitated intervention, a team or group from the organisation is usually chosen to analyse and solve a given company problem supported by the OR facilitator. Most of the steps followed by the OR facilitator are done with the client, from the problem definitions to the recommendation development. For this reason, as Schein (1998) suggests it is necessary to build a helping relationship between the OR facilitator and clients.

Franco and Montibeller (2010) also discussed some assumptions related to the facilitated mode in OR. In contrast to the expert mode, the first assumption is that the problems for the facilitated mode are socially constructed entities. Even though the facilitated mode accepts that problems are objective, their essence and importance will depend on how the client defines them subjectively. Instead of identifying the 'real problem', the OR facilitator tries to encourage the client to define the problem jointly as a team, eliminating any individual perception (Eden, 1982; Landry, 1995). The second assumption is highly related to the first one and suggests that subjectivity should not be avoided. According to the second assumption of the facilitated mode, problem description is subjective since different people may have different perceptions about the future of the organization and different objectives, especially with qualitative characteristics (Eden and Sims, 1979; Rosenhead and Mingers, 2001). The role of the OR analyst is not to choose only one perspective but instead to represent all the subjectivities in a facilitated model. The third assumption suggests that instead of looking for optimal solutions, the clients expect satisficing solutions that are more implementable. Even if the problem is too complex, the model should be simple. Usually, the OR analyst provides the client with solutions to the problem with good results that can be easily implemented (Eden and Sims, 1979; Rosenhead and Mingers, 2001). Finally, the fourth assumptions suggest that the participation of key stakeholders in the facilitated modelling and analysis increases the likelihood of the implementation of the solutions (Rosenhead and Mingers, 2001). As Franco and Montibeller (2010) suggest, the involvement of the stakeholders makes them feel more confident about the analysis performed and the resulting recommendation.

2.3.6. Facilitated modelling

Facilitation is *"a set of functions or activities carried out before, during, and after a meeting to help the group achieve its own outcomes"* (Bostrom, Anson and Clawson, 1993, p. 147). Facilitation can be done at an individual or a group level. OR facilitation usually requires a group of people from the client company. The main objective of group facilitation is to enable the group members to solve the given problem together more effectively. As Phillips and Phillips (1993) suggest, an effective facilitator is a process expert who helps the group to solve the organization's problem by making the most of the participants' individual and group knowledge about the problem while at the same time helping the group to overcome any dysfunctional dynamics.

Facilitated modelling is the process used by the facilitator to create models jointly with a group of people from a client organisation with or without the assistance of a technological tool (Eden and Radford, 1990). According to Franco and Montibeller

(2010), a formal model represents a problem that can be represented as process flow, cause-effect relationship, and the relationship between decisions and consequences. A formal model can be analysed and manipulated but is not necessarily quantifiable. Managers use facilitated models to understand the studied problem better, articulate preferences to value the outcomes of the analysis, and facilitate the implementation of the different recommendations.

Franco and Montibeller (2010) discussed main aspects of facilitated modelling: process, model, outcomes, and facilitation skills.

Facilitated modelling process

The main purpose of a facilitated modelling intervention is to support the client group in identifying the root of the problem chosen as a group, identifying potential solutions to solve the problem and their correspondent feasible action plan (Franco and Montibeller, 2010). The reasoning behind working in facilitated groups is that complex problems usually involve different stakeholders with different interests that need to interact with each other to identify the best alternative for the group instead of exerting pressure from the side of the most powerful stakeholder side (Rosenhead and Mingers, 2001).

Hence, when group members participate in the facilitated modelling process, they engage in conversations to understand the views of the other group members. The facilitated modelling process is participative. The group participants help define the problem, understand it, come up with a joint definition of the problem, and develop and select a set of solutions for the addressed problem (Franco and Montibeller, 2010). The whole process is supported by the OR researcher, who acts as a facilitator and modeller (Phillips and Phillips, 1993; Ackermann, 1996). More details of the facilitated process will be discussed in Chapter 5. Research Design.

Facilitated model

Models built in a facilitated environment help managers better understand a problem situation. Moreover, the facilitated models are a helpful tool for managers who want to explore the impact of implementing different ideas and courses of action to make informed decisions (Lane, 1992). Facilitated models usually represent relationships of ideas, processes or stakeholders. The constituents of each model will depend on the approach each facilitated group wants to take, such as evaluating options or designing systems. The model primarily aims to help structure problems and evaluate decision points (Franco and Montibeller, 2010).

Authors like Rosenhead and Mingers(2001)and Eden and Ackerman(, 2004) agree that visual methods are useful to represent complex problems that otherwise would be difficult to represent and understand using quantitative models. Facilitated models are transparent, easy to use, and use visual representations (e.g., cause-effect diagrams, decision trees, causal loop diagrams, stocks, flows). They try to use the group language and preferences to assess alternatives.

Facilitated modelling outcomes

Facilitated modelling approaches have several outcomes. Some of the modelling process outputs can be clearly visible, while others may be less visible. As Franco and Montibeller (2010) suggest, the most visible outcome of the facilitated modelling process is the model itself built in the facilitated process. The model represents the structure of the problem and allows the group of participants to do multiple experiments and analyses and draw conclusions from the simulation model results. The facilitated modelling process also has several examples of invisible outcomes. Checkland (1981), for instance, suggests that the facilitated modelling approach allows a group interaction and discussion of the problem that is represented in the model and also allows the group members to represent and adjust the multiple positions of participants. As Rosenhead and Mingers (2001) suggest, complex problems or strategic decisions usually demand participants to accommodate their expectations to consider the expectations and objectives of others. Another invisible outcome is the shared understanding of the problem situation. The manipulation of the model variables and evaluation of the solution alternatives as a group gives participants a shared understanding of the problem, the impact of the solution alternatives, other people's values, and organisational processes at different areas and levels (Rosenhead and Mingers, 2001). Such greater understanding leads to a sense of common purpose that preserves the essence of the individual opinions (Phillips, 2007). Finally, the participative nature of the facilitated modelling process generates strong ownership of the problem conceptualisation, the action plan, and the commitment to the implementation (Rosenhead and Mingers, 2001; Phillips, 2007).

Facilitative modeller skills

Facilitative modelling requires the operational researcher to do the modelling and act as a facilitator during the whole process. Franco and Montibeller (2010) discussed the essential skills to conduct an effective facilitative modelling process: active listening, chart-writing, managing group dynamics and power shifts, and reaching closure. Active listening requires the operational researcher to clarify, summarise, organise group members' ideas, validate participants' contributions without judging, and help participants keep turns when developing ideas. Another relevant skill, especially for OR facilitators that rely on manual support instead of computers, is "chart-writing" (Franco and Montibeller, 2010). The chart writing skills involve having an understandable writing style and speed to use lists, matrices, flow charts and symbols. According to Franco and Montibeller (2010), the most important skill that the OR facilitator must master is managing group dynamics and power shifts. Through active listening, the facilitators should be able to notice when complex or conflicting group dynamics start arising during the modelling development and treat it as a group situation that requires support (Franco and Montibeller, 2010). An alternative to face these situations is to encourage balanced participation, acknowledging the contributions and eliminating any source of distraction, and helping participants to get out of the "groan zone". Finally, reaching closure is an essential skill that the OR facilitator should ace to reach a final agreement between the participants to move on in the facilitation process. The facilitator needs to be prepared to identify when the group ideas have reached saturation from experimentation with the model to reach closure (Eden, 1992). Depending on the type of organisation, the facilitator should be able to identify the group members with power and authority to make decisions on the implementation of solution alternatives since they will decide if the proposal needs further discussion or if it is possible to make a final decision (Franco and Montibeller, 2010).

2.3.7. Approaches used in facilitated modelling applications using simulation

As shown in the Franco and Montibeller (2010), Facilitated modelling in operational research study, simulation techniques have been used in facilitated modelling interventions. Two of the most popular simulation tools that has been used in the past in the facilitated mode are system dynamics and Discrete Event Simulation (DES). Since the beginning, the system dynamics field has recognised the need to engage managers in modelling (Forrester, 1997). For instance, Morecroft's (1984) case study showed how the facilitated use of system dynamics could support an office equipment company team in developing a company strategy. The case study discussed how the facilitator modeller worked closely with the team of experts to develop a conceptual model. Then, the team used a system dynamics model to generate debate about the company's strategy.

Richmond (1997) was one of the authors who validated system dynamics in a facilitation context. Richmond (1997) proposed the *"Strategic forum"* that involved the participation of a senior management team supported by a facilitator modeller who guided a team following a strict process to align the business processes and the company strategy with the desired objectives using system dynamics. The management team of this study had a good understanding of the business operations and the elements required to align the business processes, objectives, and strategy (Richmond, 1997).

In Vennix's (1996) research, the term "group modelling" was used to describe the building up of a system dynamic model developed by the facilitator and a group of clients. Vennix (1996) suggested that "learning teams" are created during the facilitation process where the participants learn from their colleagues to generate shared new ideas. Richardson and Andersen (1995) conducted a research for the Rockefeller College of Public Affairs that involved a large group of clients in model formulation. The authors studied the strategies for efficient and effective model building in teams using system dynamics models with the inputs gathered in facilitated computer-aided team workshops. Some of the cases studied by Richardson and Andersen (1995) were care in New York State, Medic-aid costs in the state of Vermont, and homelessness policy initiatives in New York City.

DES is another type of simulation with mathematical foundations; however, it varies significantly from system dynamics in terms of assumptions and methodologies. Hence, as Tako and Robinson (2010) suggest, the techniques and methodologies from system dynamics cannot be transferred. DES is a tool commonly used by operational researchers that use the expert mode approach. As Banks *et al.*, (2005); Robinson (2014); and Law (2015) suggest, to do a simulation study, it is necessary to have regular meetings with clients; however, they assume that the modelling and analysis are conducted when the client is not present. Pidd and Robinson (2007) suggested that the dominant simulation development approaches are software engineering or Visual Interactive modelling, which do not require the client to be present during the whole developing process. Robinson (2002) and Pidd and Robinson (2007) were some of the first authors to recognise the suitability of discrete-event simulation in a facilitated environment. Pidd and Robinson (2007) identified two ways to use simulation in a facilitated environment. The first one is model building through participative modelling, and the other is facilitation for using (or experimenting with) the model. Robinson *et al*. (2014) argued that the aim of using simulation in a facilitated environment is to generate discussion about the problem being studied using quick and simple models that are not necessarily accurate but help generate debate and gain better insights into the problem situation. The development of the conceptual model, model coding, and experimentation with the model are repeated several times (Robinson, 2014). The clients are involved in every stage of the modelling process. The modeller does not need to be a software or modelling expert; instead, he needs to have the necessary skills to facilitate the process (Robinson *et al.*, 2014). There are a few exemplars of the application of Discrete-event simulation application using a facilitated approach (Robinson, 2001; Adamides and Karacapilidis, 2006; Den Hengst, De Vreede and Maghnouji, 2007)

Robinson (2001) used DES to study a university user support helpline. In the beginning, the author wanted to conduct an expert mode OR, but due to the lack of appropriate data, the simulation could not be used to do an objective analysis. Hence, the author run facilitated sessions with the clients, and the DES model was used to understand the helpdesk attention process and discuss potential improvement alternatives. The ideas generated at the facilitated sessions were tested by updating and running the simulation model as many times as needed. Adamides and Karacapilidis (2006) also proposed a framework and methodology for modelling collaborative business processes. The author used a facilitated approach to create a process map and report the results of a simulated version of the map. The authors created an interactive web-based information system that allowed the study stakeholders to collaborate in the process map development. In Adamides and Karacapilidis's (2006) case study, the DES simulation modelling was developed offline by an expert modeller. Then, the results of the experimentations with the model were shared with the stakeholders not to offer predictions or optimization results but instead to offer indications of how the performance of the business process may be affected.

Den Hengst, De Vreede and Maghnouji (2007) researched cargo flows in the Dutch airline industry, using OR principles to conduct a collaborative DES simulation study. One of the particularities of the research was that the authors ran several sessions throughout the project cycle to formulate the problem, build the model, validate it, do experiments and validate the findings obtained from the model. The DES simulation model in this study had a high level of detail and required around four months to develop. Consequently, the model ran slowly, and it was inappropriate to use in the facilitated meetings; however, a simplified version of the model was created for use in client meetings. Similarly to other facilitated interventions involving simulation, the simulation model's objective was to understand the process and not optimise it. As part of their study, Den Hengst, De Vreede and Maghnouji (2007) also provide some recommendations for future researchers interested in developing collaborative simulation. The first suggestion was related to the design of the simulation model. The authors suggested that non-experts must understand the model; the model has to be a valid representation of reality, easily adaptable, and run quickly. Regarding the data collection, the authors suggested that the facilitator could use expert estimations gathered in the collaborative sessions to reduce the data collection time. In the case of the model building, the time could be reduced using previous or reusable model components.

Tako, Kotiadis, and Vasilakis (2010) proposed the participatory simulation framework to develop and use DES models in healthcare. The framework proposed by the authors has six stages: beginning the study, describing the problem of interest, defining study objectives, building up simulation models, experimentation, and execution. The study's originality relies on the participative approach used in describing the problem of interest, defining study objectives, experimentation, and execution. To conduct the study, the authors Tako, Kotiadis and Vasilakis (2010) did four facilitated workshops, and in the first two workshops, the authors used soft system methodologies.

A summary of the approaches used in previous facilitated modelling research discussed above is presented in Table 2.2.

Table 2.2. Approaches used in previous facilitated modelling research (Author,2024)

Author	Objective	Modelling approach used	Important features
Richmond (1997)	-To develop the "strategic forum" that involves a meeting of a senior management team guided by a facilitator who guides the team following a structured procedure to align the business processes and the company strategy with the desired objectives.	System Dynamics	- At the end of the forum, the management team that participated had a better understanding of the business activities and a clearer idea of what needs to be done to achieve consistency between objectives, strategy and business processes.

Author	Objective	Modelling approach used	Important features
Richardson and Andersen (1995)	- To study the strategies for efficient and effective team model building with the inputs gathered in facilitated computer-aided workshops	System Dynamics	- The workshops were computer-aided - The problems studied were care in New York State, Medicaid costs in the state of Vermont, and homelessness policy initiatives in New York City
Robinson (2001)	- To use DES modelling to improve the user support helpline service at a university. - To conduct a facilitated discussion using a simulation model to assess different improvement alternatives.	Discrete-event simulation	-The study demonstrated how, despite DES being considered a hard OR technique, it could be used in a “soft” OR context. - The visual characteristics of DES allowed the decision-makers to see the representation of the process. It also allowed them to interact with the model, making them active participants in the simulation study.
Adamides and Karacapilidis (2006)	-To conduct an action research study for process improvement in organizational settings as a pilot application. -To develop a framework and methodology to conduct a facilitated business process modelling.	Discrete-event simulation	- Authors developed an interactive web-based information system that stakeholders used to collaborate in the process mapping. -The model was built off-line by an expert modeller

Author	Objective	Modelling approach used	Important features
Den Hengst, De Vreede and Maghnouji (2007)	- To study how collaborative simulation can be applied as a problem-structuring method through a case study in the Dutch airline industry.	Discrete-event simulation	- Several facilitated sessions throughout the project to define the problem, model building, validation, experimentation, and discussion of findings. - The DES model had a high level of detail that required four months to develop. A Parallel simplified model was used for the sessions.
Tako, Kotiadis and Vasilakis (2010)	-To develop a participative modelling framework that is applied to develop a conceptual model of an obesity care system	Discrete-event simulation	- The study highlights the participative approach used in describing the problem of interest, study objectives definition, experimentation and execution. The authors proposed a new modelling approach that involves stakeholders participating in the conceptual modelling process.

2.4. Reverse Supply chain design

2.4.1. RSC Definitions and research categories

The American Reverse Logistics Executive Council defines Reverse Logistics (RL) as *"the process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal"* (Rogers and Tibben-lembke, 1999, p.2). On the other hand, a reverse supply chain is defined as a group of activities performed to recover products that customers no longer use and reprocess them to recover part of their value or dispose of them (Guide Jr. and Van Wassenhove, 2002; Gupta, 2012). Therefore, it has a broader scope and includes the activities performed by other supply chain members. When the forward and reverse supply chains are considered together, the Closed-Loop Supply Chain (CLSC) is created. One of the most popular definitions of Closed-Loop Supply Chain

Management is the one given by Guide and Wassenhove (2009), which define it as *"the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time"(p.10)*.

As many authors suggest, an alternative to ensure the sustainability of supply chains and assure its economic viability is the development of reverse supply chains (RSC) and closed-loop supply chains (CLSC) (Govindan, Soleimani and Kannan, 2015; Kazemi, Modak and Govindan, 2019). As Carter and Ellram (1998) suggest, RSC is a relevant topic for academics and practitioners because it adds value to supply chains and makes them more sustainable. As shown in the systematic literature review conducted by Kazemi, Modak and Govindan (2019), the interest in the concepts of RSC and CLSC can be evidenced in the more than 800 academic publications that have been published during the last decades. According to Kazemi, Modak and Govindan (2019), the most researched study subjects within the RL, RSC and CLSC literature are network design and planning (see for examples, Jayant, Gupta and Garg, 2014; Jindal and Sangwan, 2014), followed by survey (see for examples, Dowlatshahi, 2010; Abraham, 2011) and price and coordination (see for examples, Chen and Chang, 2012; Zhao, Liu and Wei, 2013). As Kazemi, Modak and Govindan (2019) suggest, the network design research aims to find the best configuration able to collect used or faulty products and reprocess them through recycling, remanufacturing or repurposing efficiently.

2.4.2. Approaches used in previous RSC design research work

According to the literature, some of the approaches that have recently been used to address the design of RSC and CLSC issues have been linear programming, non-linear programming, and simulation. Some exemplars of the application of linear programming on RSC and CLSC design are the pieces of work developed by Jindal and Sangwan (2014) and Ghorbani, Arabzad and Tavakkoli-Moghaddam (2014).

Jindal and Sangwan (2014) proposed a Closed-loop supply chain framework in an uncertain context that may be used to analyse configurations with multiple products and facilities. As part of their research, the authors developed a generalized framework that includes the forward and reverse flow as well as the main interactions among entities. As may be seen in Figure 2.3, the authors' network has a five-stage forward supply chain (raw-material suppliers, plants, distributors, retailers and customers) and a five-stage reverse supply chain (collection/repair centres, disassembly centres, refurbishing centres, recycling centres and disposal centres) (Jindal and Sangwan, 2014). This model also considers multiple collections, disassembly, and refurbishing centres and allocates the optimal number of product parts to be processed. As Jindal and Sangwan (2014) suggested, the demand for products, costs, and percentage of parts recovered for reusing, refurbishing, recycling, or disposal are uncertain (Jindal and Sangwan, 2014). For this reason, the authors used fuzzy numbers to characterise the uncertainty of the demand levels, returns, and transport and process costs; based on that information proposed a fuzzy mixed integer linear-programming (FMILP) model that maximises profit.

The model's usefulness was tested with an illustrative example with fabricated data. The example was solved using Lingo 13 optimization tool (Lindo Systems, 2020). However, as the authors suggested, for large real industry problems, this methodology could not be used directly and may need more sophisticated techniques (Jindal and Sangwan, 2014).

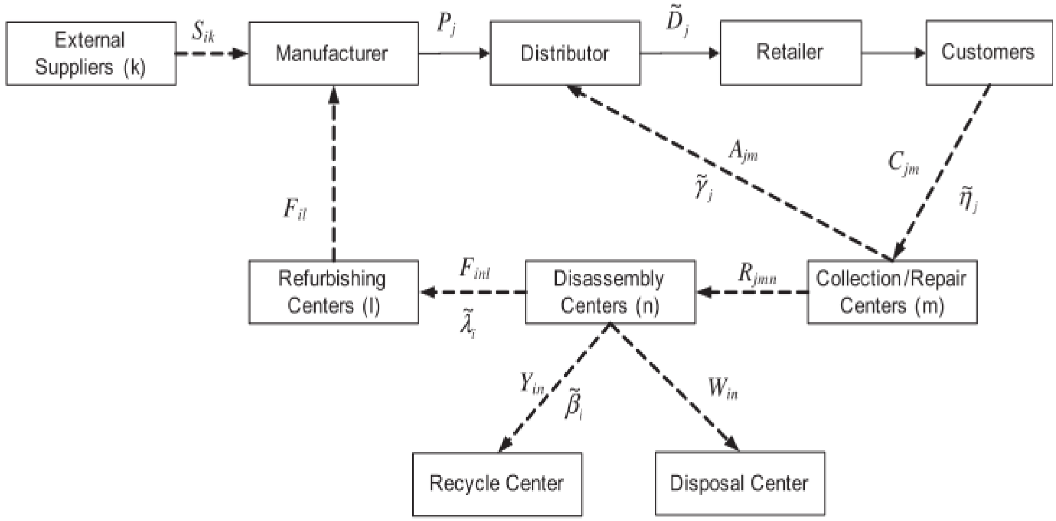


Figure 2.3. CLSC framework (Jindal and Sangwan, 2014)

Similarly, Ghorbani, Arabzad and Tavakkoli-Moghaddam (2014) proposed a fuzzy goal programming-based approach for a linear programming model to address the reverse supply chain design issue. However, in contrast to Jindal and Sangwan (2014), who used a single optimization model, Ghorbani, Arabzad and Tavakkoli-Moghaddam (2014) proposed a multi-objective optimization. The proposed model solves the location-allocation problem of recyclers, considering green supply chain goals. To choose the best recyclers, the three objectives to be minimised were recycling cost, waste rate, and material recovery. The model used a fuzzy goal programming-based approach and incorporated the opinion of the decision-makers to make the correspondent trade-offs between objectives. To demonstrate the benefits of the proposed model, Ghorbani, Arabzad and Tavakkoli-Moghaddam (2014) solved an illustrative case with five product types and twelve recyclers using Lingo 9.0.

As was stated previously, another strategy to address the RSC and CLSC design research is non-linear programming. In contrast to other studies, Das and Dutta (2015) developed a model that considers consumers' buying patterns and willingness to accept an offer to return a used product aligned with the number of used products that may be returned. The model proposed by Das and Dutta (2015) was built for a single product and maximised the profit of the network configuration by identifying the optimal discount that could be offered to clients, optimal quantity to be manufactured, remanufactured, and disposed of, as well as the ideal transportation and inventory levels. This study is novel since it proposes a market-driven recovery framework to improve the collection and recovery process in a CLSC from a marketing-operation perspective. According to the findings, using a promotional offer to increase the collection rates does not only helps meet the legislation requirement but also helps increase the profits of remanufacturing products (Das and Dutta, 2015).

Finally, simulation is another important approach that has been used to address the main RSC issues. Jayant, Gupta and Garg (2014) developed a simulation model of a reverse logistic network for an Indian lead metal manufacturer with a battery recycling plant that processes batteries that have reached their EoL. Some of the main problems identified in the reverse logistic network of the lead metal manufacturer were the following:

- The supply of batteries was not regular; therefore, it was difficult to forecast the collection times.There was no defined reverse logistic network.
- The company did not use any performance indicators to assess reverse logistics.
- The reverse supply chain workstations were underutilized.

To solve these problems, the authors proposed developing a Reverse Logistic Network simulation model of forward and reverse supply chain (Figure 2.4.) to predict future performance.

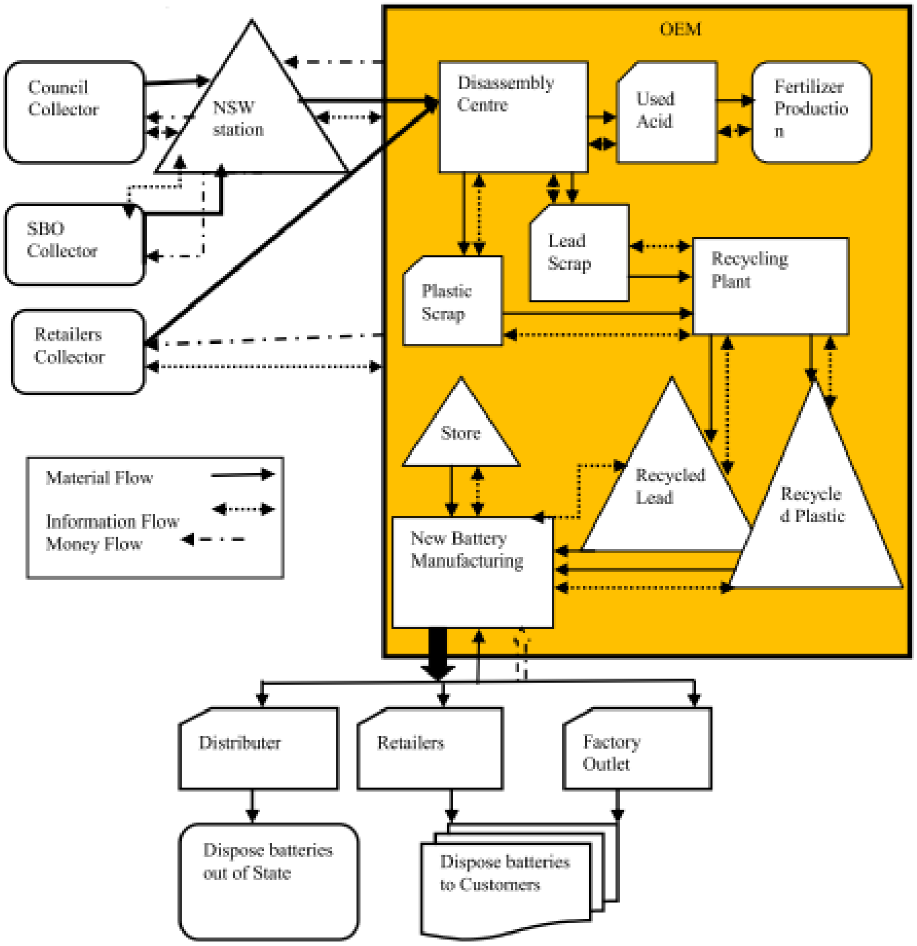


Figure 2.4. Reverse Logistic Network (Jayant, Gupta and Garg, 2014)

The proposed simulation model was developed using Arena 11.0 simulation package (Rockwell Automation, 2020). The model developed included the main supply chain participants involved in the reverse logistic processes, such as the companies in charge of collection, OEMs and clients of the new batteries produced (e.g. distributors, retailers, factories, outlets). The model developed by Jayant, Gupta, and Garg (2014) calculates cycle time, transfer time, cost, service level, and resource utilization. The study results suggest a significant improvement in the reverse logistics network performance and product supply planning (Jayant, Gupta and Garg, 2014).

Likewise, Yanikara and Kuhl (2015) proposed a general simulation framework to assess various reverse logistic configurations and identify the best option according to productivity and sustainability metrics. A discrete-event simulation modelling approach was chosen since it allowed the design of a highly flexible model to represent a variety of system configurations (Yanikara and Kuhl, 2015). This model differed from other reverse logistic network models because of its practical implications and ease of use (Figure 2.5).

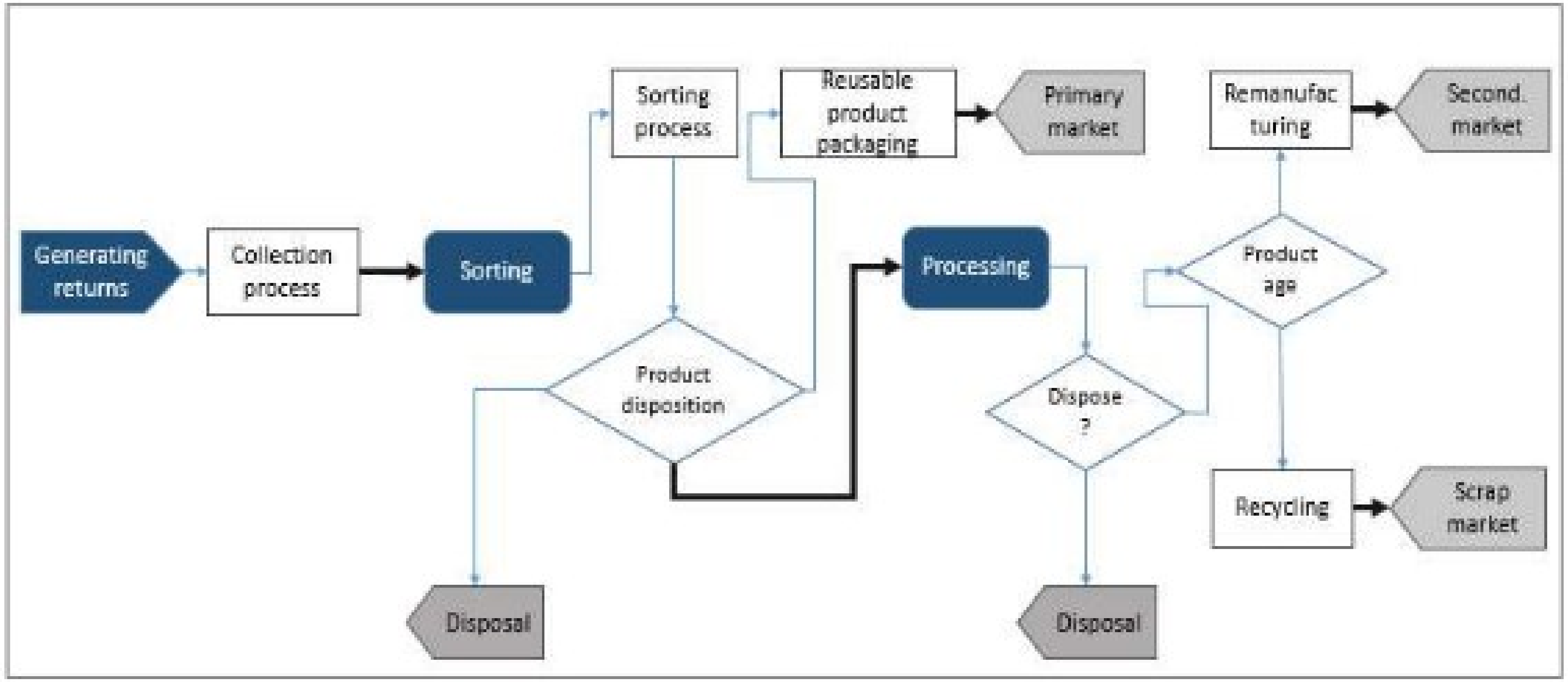


Figure 2.5. Process flows in the simulation model (Yanikara and Kuhl, 2015)

The simulation software chosen to develop the model was Simio (Simio LLC, 2020), complemented with an MS Excel user interface to add the specifications of the system and network configuration parameters. In addition, the results were displayed in an MS Excel spreadsheet. The model was built by the authors based on the thinking of academics and practitioners who are not simulation experts so they can still use the model and adapt it to represent reverse logistic networks of a variety of products in different industries. Moreover, the proposed model provides an assessment of the performance of such network configurations in terms of productivity and sustainability metrics, which, according to Govindan, Soleimani and Kannan (2015) has not been included much in the literature. The productivity and sustainability metrics used in this study are transport cost, collection/sorting/processing cost, inventory cost, disposal cost, time in the system, the value of recovery, and emissions. Like most of the RSC and CLSC papers reviewed, Yanikara and Kuhl (2015) provide an exemplar case to illustrate the tool functionality through an experiment with six scenarios using a fictitious data set. To compare the different scenarios, each metric is assigned a weight factor to simplify the comparison. However, as in other studies, the illustrative case is arguably too simple to reflect a real industry case scenario.

A summary of the Reverse Supply Chain and Closed Loop supply chain design papers discussed above is presented in Table 2.3.

Table 2.3. Summary of commonly used strategies for RSC and CLSC design (Author, 2024)

Author	Objective	Method Used	Does it reflect an industry case?	Important features
Jindal and Sangwan (2014)	- To develop a Closed-Loop Supply chain framework to analyse configurations with multiple products and facilities. - Use of fuzzy numbers to characterise the uncertainty of some variables; a fuzzy mixed integer linear-programming (FMILP) model that maximises profit is proposed	Linear programming with a single optimization	No. An illustrative case was presented, but the methodology is not helpful for real industry problems	- Five stage reverse supply chain (collection/repair centres, disassembly centres, refurbishing centres, recycling centres and disposal centres). - Model maximizes profit - Represent the variability for the demand of products, costs, and percentage of parts recovered for reusing, refurbishing, recycling or disposal

Author	Objective	Method Used	Does it reflect an industry case?	Important features
Ghorbani, Arabzad and Tavakkoli-Moghaddam (2014)	- To develop a linear programming model using a fuzzy goal programming-based approach to solving the location-allocation problem of recyclers. - Use of a multi-objective optimization that considers cost, time and efficiency metrics (e.g. recycling cost, rate of waste generated by recyclers and material recovery time)	Linear programming with multi-objective optimization	No. A numerical example with created data is conducted to show the effectiveness of the model	- The reverse supply model includes manufacturers and recyclers. - Use cost, time and efficiency metrics.
Das and Dutta (2015)	- To develop a model that considers consumers' buying patterns and willingness to accept an offer to return a used product aligned with the number of used products that may be returned. -The model was designed for a single type of product and maximised the profit of the network configuration	Non-linear programming	No industry case study. A comparative numerical study has been conducted to examine the performance of the CLSC with vs without a promotional offer.	- It proposed a market-driven recovery framework that models the consumers' willingness to return the used product as a function of the discount amount offered to the consumer.

Author	Objective	Method Used	Does it reflect an industry case?	Important features
Jayant, Gupta and Garg (2014)	To develop a simulation model of a reverse logistic network for an Indian lead metal manufacturer with a battery recycling plant that processes batteries that have reached their EoL.	Simulation	Yes. Case study of a Lead metal Manufacturer/ recycler of batteries	- Reverse Logistic model includes companies in charge of collection, OEMs and clients of the new batteries produced (e.g. distributors, retailers, factories, outlets). - The model calculates cycle time, transfer time and cost, service level and resource utilization.
Yanikara and Kuhl (2015)	- To develop a general simulation framework to assess various reverse logistic configurations and identify the best option according to productivity and sustainability metrics -A discrete event simulation modelling approach was chosen to represent a variety of system configurations.	Simulation	No. It uses a simple illustrative case that does not reflect the characteristics of a real industry case	-The simulation model is practical and easy to use by non-experts - The model has an MS Excel user interface to add the specifications of the system and network configuration parameters. The results can be visualized in the MS Excel spreadsheet. -Moreover, it uses productivity and sustainability metrics (e.g. Transport cost, collection/sorting/processing cost, Inventory cost, Disposal cost, time in the system, the value of recovery, emissions.)

2.5. Business relationships in the RSC

2.5.1. Relationships nature in the supply chain

As Sorker (2008) suggests, limited literature describes the relationship between reverse supply chain actors. For this reason, some of the general supply chains relationships are presented. There are different ways to classify the relationship types between companies in a supply chain. For instance, Lambert, Emmelhainz and Gardner (1996) suggest that the relationships between organisations can go from arm's length (one time or multiple transactions with adversarial relationships) to vertical integration of firms, as shown in Figure 2.6.

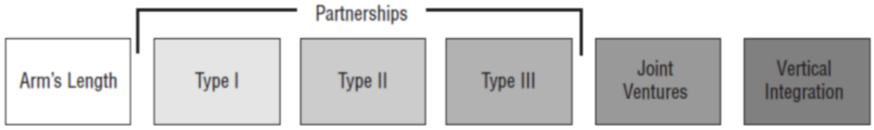


Figure 2.6. Types of relationships (Lambert, Emmelhainz and Gardner, 1996)

According to Lambert, Emmelhainz and Gardner (1996), in an arm’s length relationship, the organisations do not have a sense of joint responsibility. In an arm’s length relationship, the seller offers a standard product or service to different clients under standard conditions. Once the transaction finishes, the relationship finishes. In contrast, a partnership is a relationship that requires trust, risk sharing and reward sharing that results in a better performance than the one that would be achieved if the companies worked separately (Lambert, Emmelhainz and Gardner, 1996). As Lambert, Emmelhainz and Gardner (1996) suggest, no ideal type of partnership exists that every company can replicate. Each relationship has different drivers, context, duration, strength, and the closeness of the partnership will vary over time. In Lambert, Emmelhainz and Gardner's (1996) research, the authors identified three types of partnerships (Figure 2.6). In the type I partnership, the companies identify themselves as partners and coordinate actions and plans at a superficial level. Type I partnership focuses on the short term and usually involves a single division or department in each company. In contrast, in a type II partnership, the firms move from coordination to integration of activities in several divisions and departments for a long-term period. In the case of a type III partnership, the companies are integrated at an operational level, and each firm views its partner as an extension of its firm. As Lambert, Emmelhainz and Gardner (1996) suggest, type III partnership should be limited to suppliers that provide critical products or services for a firm’s success.

Cox (1996) proposed a different model to classify the suppliers' relationship called *“A stepladder of external and internal contractual relationships”* (See Figure 2.7.). In this model, the different steps of the ladder represent a higher level of asset specificity and the strategic importance of the specific goods and services to the firm. Each step also represents relative degrees of power between the companies' relationships. The ladder starts with an adversarial relationship, which is always arm’s length. In an arm's length relationship, the supplier does not need to understand the purchasing company or its business objective, and neither has to add value above. Arm’s length relationships are associated with low asset specificity and low supplier competencies that can easily be bought off the shelf as there are many potential suppliers. The preferred suppliers are considered the best option to provide complementary goods or services, but they are at the lower end of the ladder because of their low importance to the firm. The firm usually selects a restricted number of suppliers after using vendor rating or accreditation to choose a preferred supplier. Single sourcing is the relationship built when a company buys from a single supplier of medium asset specificity complementary goods or services of relatively high strategic importance. As Cox (1996) observes, single sourcing aims to reduce transaction costs and economise without the costs associated with vertical integration. The aim of single sourcing is to reduce transaction costs and economise but without the costs associated with vertical integration. Network sourcing and partnerships rely on the idea that it is possible to create a virtual company at all levels of the supply chain by establishing multiple-tiered partnership relationships at each stage but without moving to vertical integration. Cox (1996) defines strategic supplier alliances or joint ventures as 'negotiated single-sourced relationships with the supplier of a complementary product or service'. This relationship forms an entirely new and independent legal entity, distinct from the firms that form the alliance. Both parties have some degree of proprietorship (not necessarily 50/50) in the outcome of the relationship. Strategic supplier alliances are the final stage before a firm considers a complementary supplier so important that vertical integration through merger and acquisition is undertaken.

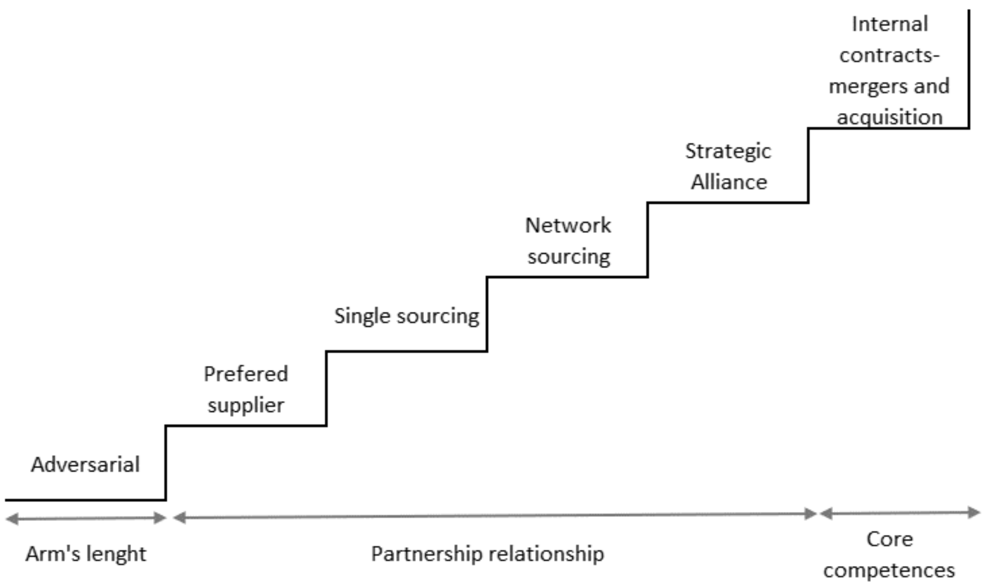


Figure 2.7. A stepladder of external and internal contractual relationships (Cox, 1996)

According to Harrison and van Hoek (2008), in the supply chain context, the term partner can be applied to any firm involved in a supply chain network. A strategic partner refers to *"a supply chain partner with whom a focal firm has decided to develop a long-term collaborative relationship"*. As Harrison and van Hoek (2008) suggest, collaboration can be the ultimate relationship goal for supply partners. However, to get there, the supplier relationship needs to pass through different stages. Spekman, Kamauff, and Myhr (1998) proposed a transition route with the requisites to transition from an important supplier to a strategic supply chain partner (See Figure 2.8). According to Figure 2.8, the partners start with open market negotiations, then move on to co-operate, coordinate, and finally collaborate. As the authors suggest, the transition follows a linear route, but it could also be outlined with steps since moving from one stage to another requires that partners change their mindsets and have a strategic orientation. Open market negotiations involve adversarial relationships between partners based on price. In the case of cooperation, the number of suppliers reduces, start sharing limited information and the contracts have a long-term view. In the coordination stage, workflow and information are exchanged, allowing JIT (Just in Time) and EDI (Electronic Data Interchange) (Spekman, Kamauff and Myhr, 1998). Spekman, Kamauff and Myhr (1998) argue that several companies have already achieved cooperation and coordination with suppliers and clients; however, to move to the collaboration level, firms need a higher level of trust, responsibility and information sharing between the partners than in the previous stages. At a collaboration level, the partners start integrating and getting involved in joint planning and technology sharing.

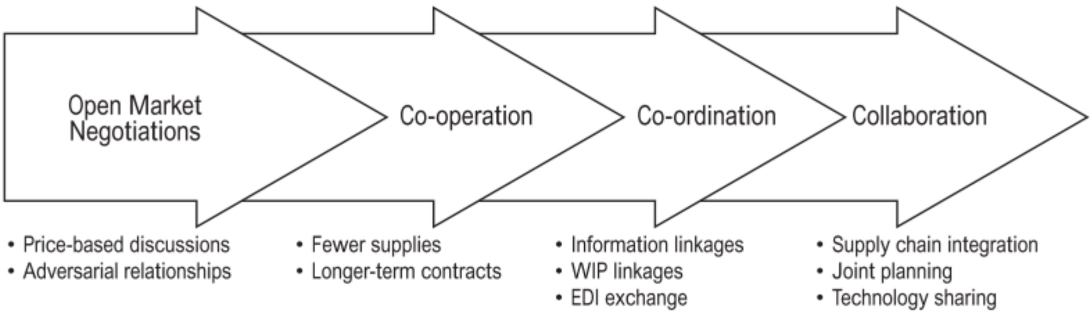


Figure 2.8. The key transition from open-market negotiations to collaboration (Spekman, Kamauff and Myhr, 1998)

2.5.2. Approaches used in previous business relationships in RSC research work

Supply chain relationships require a pair or a group of organisations that work together to get results that cannot be obtained working alone (Daugherty, 2011). In the supply chain context, the development of relationships such as coordination and collaboration enables joint planning and exchange management, execution and performance information sharing (Simatupang, Wright and Sridharan, 2002; Airike, Rotter and Mark-Herbert, 2016). As Wu, Chuang and Hsu (2014) suggest, collaboration has become essential due to the complex nature of supply chains and the number of partners involved. As Ashby, Leat and Hudson-Smith (2012) suggest, that sustainable supply chain research has focused on tangible processes andonly a few papers have recognised the relevance of building relationships within CLSCs. There are hundreds of papers that have addressed the relationships in the forward supply chain; however, as Jayant, Gupta and Garg (2012); Flygansvaer, Dahlstrom and Nygaard (2018); Cricelli, Greco and Grimaldi (2021) and Sudusinghe and Seuring (2022)suggest, only a few pieces of research have addressed the relationship in circular supply chains and reverse supply chains.

Sudusinghe and Seuring (2022) did a systematic literature review where they studied how collaboration has helped supply chain partners to acquire a sustainable performance and transition towards circular supply chains. They divided the papers reviewed into three main categories: internal collaboration, external vertical collaboration, and external horizontal collaboration. As Sudusinghe and Seuring (2022) suggest, internal collaboration refers to the operational collaboration within a firm. Vertical collaboration involves collaboration with suppliers, customers, and service providers. In a horizontal collaboration, other organizations such as competitors or other external parties collaborate. As shown in the systematic literature review conducted by Sudusinghe and Seuring (2022) one of the prominent types of collaboration addressed in the circular supply chain literature is external vertical collaboration. Some of the most popular collaborative practices applied have been information sharing with suppliers/customers, sustainability penalties and incentives, and shared responsibility for the recovery of products product design.

One relevant paper from Flygansvaer, Dahlstrom and Nygaard (2018) discussed the relationships in the reverse supply chain from an industry perspective. Flygansvaer, Dahlstrom and Nygaard (2018), studied the productive management of a reverse supply chain in the electronics industry. The research used agency theory and studied the relationship between the recycler (i.e., principal) and collectors (i.e., agents). Figure 2.9

shows the antecedents and consequences of the interfirm sustainability-oriented culture studied by Flygansvaer, Dahlstrom and Nygaard (2018). According to the findings, shared vision and ecological orientation are interfirm culture components, and the principal leadership and collaboration with agents enhance the interfirm culture. In addition, interfirm culture improves the agent's ecological performance, recycling practices, economic performance, and satisfaction. Hence, the interfirm culture positively impacts the sustainability performance of the reverse supply chain (Flygansvaer, Dahlstrom and Nygaard, 2018).

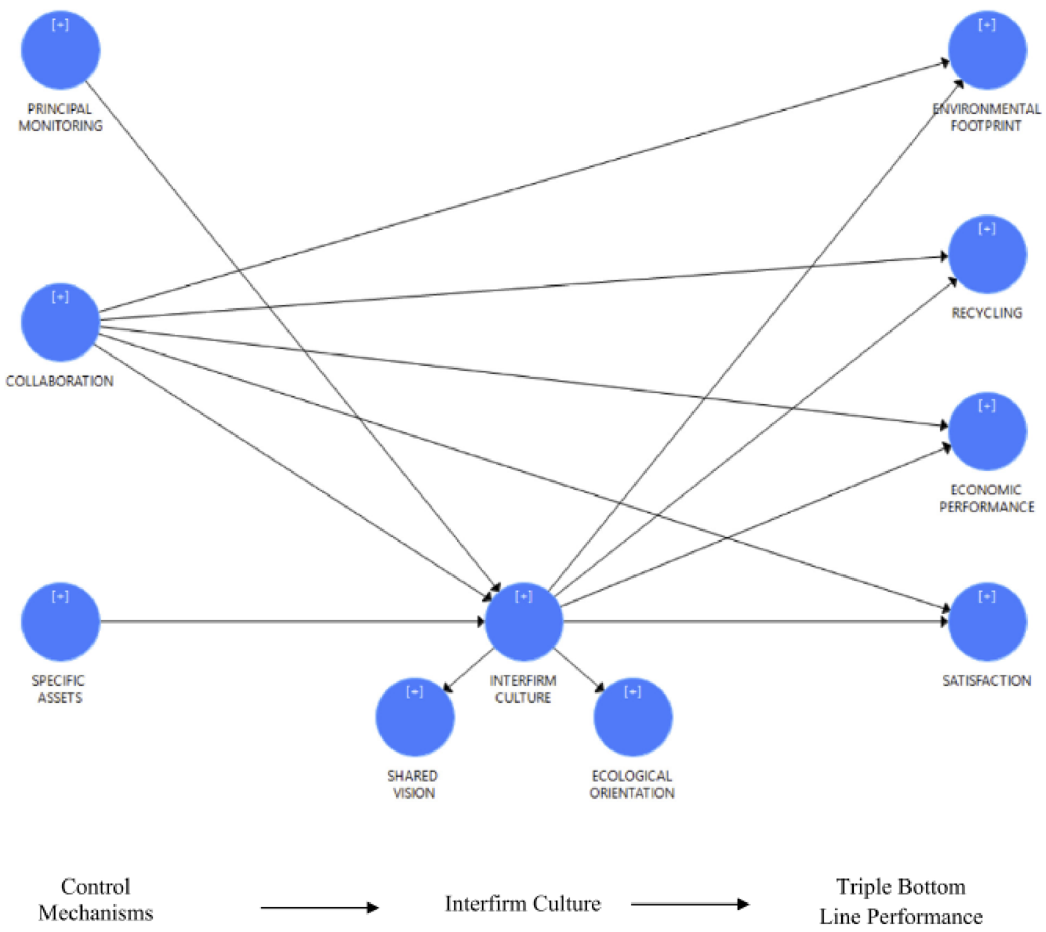


Figure 2.9. Proposed antecedents and consequences of interfirm sustainability-oriented culture (Flygansvaer, Dahlstrom and Nygaard, 2018)

Lind, Olsson and Sundin (2014) conducted research to investigate how remanufacturers manage their inter-organizational relationships and the suitability of collaboration in closed-loop supply chains. The authors conducted a case study that involved small and medium European automotive component remanufacturers. They studied and evaluated the most common relationships between remanufacturers of car components and core suppliers such as independent dealerships, scrap yards, core brokers and OEMs (See

Figure 2.10). The study findings suggest that the main problem that remanufacturers experienced in their relationships with suppliers was not receiving the exact number of cores requested. This situation forced the remanufacturers to negotiate with other customers or buy spare parts to be able to deliver their customers’ demands, causing a reduction in their profit margin. (Lind, Olsson and Sundin, 2014). The most common core suppliers identified in the closed loop supply chain of this study are independent car dealerships, scrap yards, core brokers, and OEMs. The most popular relationships identified between the remanufacturers and their core suppliers were buy-back, deposit-based and “reman-contract”. In a buy-back relationship, a business sells a product and agrees to buy it back again. While in a deposit-based relationship, when the customer buys a product, it needs to return a similar product. The reman-contract is a type of relationship identified in the case study that consists of the OEMs providing the desired cores but keeping the ownership of the cores, while the remanufacturers are only responsible for the remanufacturing activities (Lind, Olsson and Sundin, 2014). The study's findings suggest that the reman-contract relationship is the relationship that increases the order fullfilment rate and allows remanufacturers to have a better flow of cores.

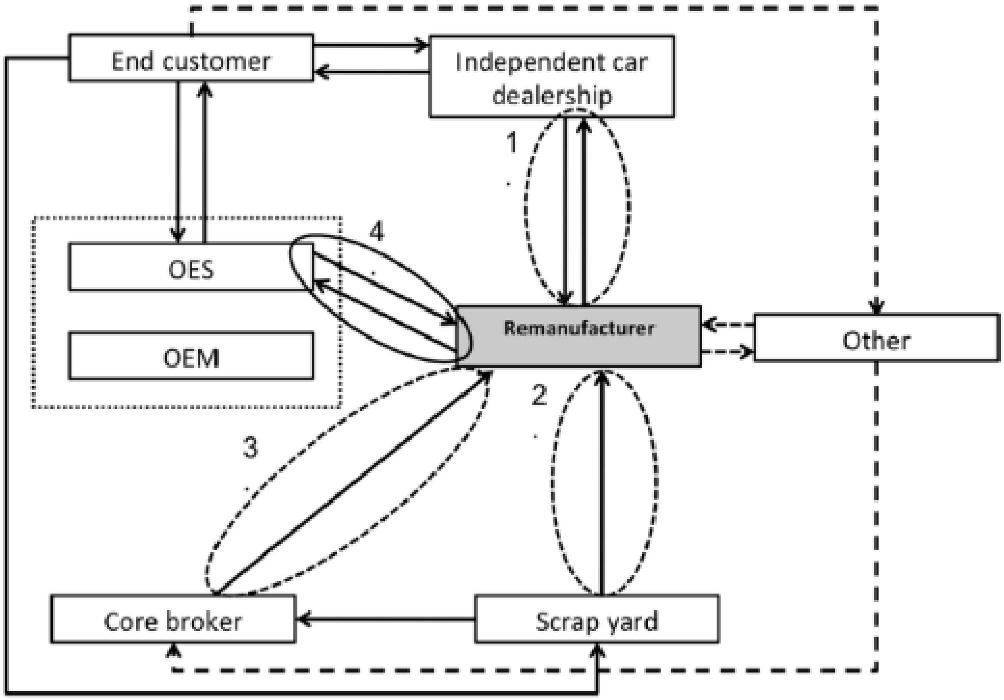


Figure 2.10. Relationships identified between the actors in a closed-loop supply chain (Lind, Olsson and Sundin, 2014)

Govindan *et al.* (2019) also did research that focused on the electronic industry. The authors' study aimed to identify the most important attributes of an OEM to collaborate with third-party reverse logistics providers (3PRLPs) sustainably. The researchers proposed an integrated framework that can be used by 3PRLPs that collect used electronic products to assess the attributes of OEMs in terms of the economic, environmental, and social attributes of sustainability for potential collaboration. Govindan *et al.* (2019) used the Complex Proportional Assessment (COPRAS) to pre-evaluate the attributes. Then, the shortlisted attributes for each sustainability dimension are evaluated and prioritized using the best-worst method (BWM). As the authors suggest, the methodology and results of this research may be used by the different reverse supply chain entities interested in assessing potential collaboration partners with aligned goals and objectives.

A summary of the approaches used in previous business relationships in RSC research work papers discussed above is presented in Table 2.4

Table 2.4. approaches used in previous business relationships in RSC research (Author, 2024)

Authors	Objective	Approach used	Does it reflect an industry case?	Important features
Sudusinghe and Seuring (2022)	- To examine how collaboration in developing circular supply chains may improve sustainability performance - To develop a conceptual framework that supports the identification of the best collaboration practices to enhance relationships that improve sustainability.	Systematic literature review	No. This research does not focus on one particular industry. However, it discusses the different types of collaboration practices to improve sustainability discussed in academic papers.	- This paper discusses the contribution of different supply chain collaboration practices towards achieving the three dimensions of sustainability performance (economic, social, environment) -This study looks beyond the dyadic business relationships and takes a multi-tier supply chain perspective, including external parties (e.g. government, NGOs).
Flygansvaer, Dahlstrom and Nygaard (2018)	- To understand the productive management of reverse supply chains. - To illustrates the role that an interfirm culture plays in the reverse supply chain.	Principal-agency approach where control structures are antecedent to the shared culture between the recycler (i.e. the principal) and its collectors (i.e. the agents).	Yes. This research studies the relationships in the reverse supply chain of the electronic industry.	- This study analyses a supply chain that has been successful on directing a high volume of material from disposal thanks to its reverse supply chain.

Authors	Objective	Approach used	Does it reflect an industry case?	Important features
Lind, Olsson and Sundin (2014)	-To investigate how remanufacturers manage their inter-organizational relationships in closed-loop supply chains.	Case study approach	Yes. The study involves small and medium European automotive component remanufacturers.	-The authors identified in the case study the reman-contract, which is a type of relationship that consists of the OEMs providing the cores to remanufacturers but keeping the ownership of the cores; while the remanufacturers are only responsible for the remanufacturing activities. -According to the findings, this type of relationship helped remanufacturers increase the fulfilment rate and OEMs to have a better flow of cores.
Govindan *et al.* (2019)	-To identify the most important attributes of an OEM to collaborate with 3PRLPs sustainably. - To develop an integrated framework that can be used by 3PRLPs that collect used electronic products to assess the attributes of OEMs in terms of the economic, environmental, and social attributes of sustainability for potential collaboration.	Simulation	Yes. The electronic industry	- This study identifies the performance attributes for evaluating the OEMs by 3PRLPs for a collaborative reverse logistics venture. - The researchers used the COPRAS to pre-evaluate the attributes. Then the shortlisted attributes for each sustainability dimension are evaluated and prioritized using the BWM.

2.6. EV sector development

After centuries of the absolute dominance of the internal combustion engine (ICE) as a vehicle powertrain, the electrification of the automotive sector has become more relevant due to the pressures to make transport services more sustainable (Klör, Bräuer and

Beverungen, 2014). Electric vehicles are considered a more sustainable alternative than petrol or diesel cars since they produce fewer greenhouse gasses and air pollutants in the use-phase of operations (EDF, 2019).

2.6.1. Global sales of electric vehicles and future outlook

The popularity of electric vehicles has increased significantly during the last decades. In 2017, global sales surpassed the 1 million units for the first time (Deloitte LLP, 2019), representing a growth in new electric car sales of 54% compared with 2016 (International Energy Agency, 2018). According to the latest Global EV Outlook Report (International Environmental Agency, 2024), around 14 million electric cars were sold in 2023, representing a 35% increase over the previous year. The report suggests that in Europe, in particular, new electric vehicle registrations approached 3.2 million in 2023, an increase of over 20% compared to 2022. The sales trend of electric vehicles in Europe is expected to continue growing as European union and UK have imposed bans on the sale of new petrol and diesel cars from 2035 (European Parliament, 2022; Reuters, 2023)

2.6.2. OEMs electrification strategies

OEMs have realized the importance of developing new EV models and increasing EV share and sales. For this reason, car manufacturers such as Volkswagen, BMW and Ford have announced that they will continue developing new electrification business strategies to increase EV sales and broaden the product range in the next ten years. German OEMs are the companies with the most ambitious targets. Volkswagen, for instance, is planning to sell around 22 million EVs between 2020 and 2030 and develop 80 new models by 2025 (International Energy Agency, 2019). BMW is also planning to increase electric car sales, reach an EV sales share of 15-25% by 2025, and develop 25 new EV models (International Energy Agency, 2019). The company with the most ambitious EV sales share is Volvo, which is expecting to reach 50% of EV sales by 2025. While the American company Ford has announced that it will develop 40 new EV models in the next few years (International Energy Agency, 2019). A list that summarizes the main OEM announcements related to electric cars may be seen in Table 2.5.

Table 2.5. OEM announcements related to electric cars (International Energy Agency, 2019)

Original equipment manufacturer	Announcement
BMW	15-25% of the BMW Group's sales in 2025 and 25 new EV models by 2025.
BJEV-BAIC	0.5 million electric car sales in 2020 and ***1.3 million electric car sales in 2025***.
BYD	0.6 million electric car sales in 2020.
Chonquing Changan	***21 new BEV models and 12 new PHEV models by 2025, 1.7 million sales by 2025 (100% of group's sales)***.
Dongfeng Motor CO	6 new EV models by 2020 and 30% electric sales share in 2022.
FCA	***28 new EV models by 2022.***
Ford	40 new EV models by 2022.
Geely	1 million sales and 90% of sales in 2020.
GM	20 new EV models by 2023.
Honda	15% electric vehicle sale share in 2030 (part of two-thirds of electrified vehicles by 2030, globally and by 2025 in Europe).
Hyundai-Kia	12 new EV models by 2020.
Mahindra & Mahindra	0.036 million electric car sales in 2020.
Mazda	One new EV model in 2020 and 5% of Mazda sales to be fully electric by 2030.
Mercedes-Benz	0.1 million sales in 2020, ***10 new EV models by 2022 and 25% of the group's sales in 2025.***
Other Chinese OEMs	7 million sales in 2020.
PSA	0.9 million sales in 2022.
Renault-Nissan-Mitsubishi	12 new EV models by 2022. Renault plans 20% of the group's sales in 2022 to be fully electric. Infiniti plans to have all models electric by 2021.
Maruti Suzuki	A new EV models in 2020, ***35 000 electric car sales in 2021*** up to ***1.5 million in 2030.***
Tesla	Around 0.5 million sales in 2019 and a new EV model in 2030.
Toyota	**More than** ten new models **by the early 2020s** and 1 million BEV and FCEV sales **around** 2030.
Volkswagen	0.4 million electric car sales in 2020, up to ***3 million electric car sales in 2025***, 25% of the group's sales in 2025, 80 new EV models by 2025 and ***22 million cumulative sales by 2030.***
Volvo	50% of group's sales to be fully electric by 2025.

2.7. Electric vehicle battery industry challenges

2.7.1. Electric vehicle batteries and their environmental impact

According to Goldman Sachs (2024), even though batteries have become cheaper, their analysis shows that they account for one-third of the vehicle's cost.

. China is a leader in the EV industry in EV production and the supply of components such as lithium-ion battery (LIB) cells and electric motors (Hertzke, Muller and Schenk, 2017). China is one of the most important lithium-ion battery (Li-ion battery) cell producers and accounted for 25% of the global market share in 2016 (Hertzke, Muller and Schenk, 2017). However, Japan is still ahead in li-ion battery cell production with 48% of the market share, followed by South Korea, which accounts for 27% Li-ion battery cell market (Hertzke, Muller and Schenk, 2017).

Electric Battery manufacturers such as BYD and CATL (Chinese); LG Chem, Samsung SDI, SK Innovation (Korean) and Panasonic (Japanese) are responding to the electrification trend by making significant investments in their companies. These investments are essential to responding to the growing demand that several companies have faced during the last few years. Moreover, leading companies such as the leading German OEMs are looking to have a reliable supply of electric batteries (International Energy Agency, 2019).

The capacity of electric vehicle batteries reduces with the passing of the years due to the cells' degradation and growth of the internal resistance (Klör, Bräuer and Beverungen, 2014). Therefore, EV batteries should be swapped when their state of health (SOH) drops below 80% of the initial capacity to maintain the driving range and general driving characteristics. (Klör, Bräuer and Beverungen, 2014). According to Etxandi-Santolaya (2024, depending on the type of battery and users' driving habits, batteries typically last 10 years. However, after reaching the end of their first life, electric vehicle batteries still have enough capacity to be used in a second life that demands less capacity (Klör, Bräuer and Beverungen, 2014). Taking into consideration the EV sales growth and the EV lifespan Richa *et al.* (2014) predicted that as many as 0.33–4 million metric tons of LIBs from EVs are estimated to reach their end-of-life between 2015 and 2040, and this number is expected to keep growing as the EV sales continue. According to these projections, EV batteries are likely to be one of the main contributors to the waste of lithium-ion batteries in the coming decades.

The extraction of raw materials for EV batteries and manufacturing batteries and electricity use harms the environment (e.g. pollution, supply chain CO_2 emissions, landscape destruction, natural ecosystems disruption and contamination of water resources) (International Energy Agency, 2019). This section focuses particularly on the potential impact of the disposal of electric vehicle batteries. When any waste is disposed to the landfill, there is a chance chemical content of the waste may leach into solution. Moreover, when waste begins anaerobic decomposition and water reaches the landfill, it extracts the chemicals that produce organic acids (Renou *et al.*, 2008; Kjeldsen *et al.*, 2010). In the case of Li-ion batteries, the primary leachable metals are lithium, cobalt and nickel. These elements are inside the batteries' cathodes, which are usually protected by a case; however, when the casing is degraded or broken, the inorganic elements inside may be exposed (Winslow, Laux and Townsend, 2018). As Li *et al.* (2009) suggest, landfill leachate can transport pollutants components outside the landfill and cause harm to humans and the environment (Dubey, Townsend and Solo-gabriele, 2010).

Li-ion battery waste may also contaminate the water supplies when discarded in uncontrolled open dumps. For this reason, several countries have established measures to protect landfills from receiving hazardous waste. Lithium, for instance, affects the central nervous system causing psychological disorders (Aral and Vecchio-Sadus, 2008). Another element that may leach from lithium-ion batteries is cobalt. Even though cobalt is present in B12, the intake of free cobalt may cause cancer (Leonard, Hantson and Gerber, 1995). Other metals such as copper, iron and nickel have been found to damage DNA and cause premature ageing (Mehta, Templeton and Brien, 2006).

2.7.2. EV batteries EoL management and Circular Economy

EV batteries EoL management is essential to ensure the sustainability of the raw material supply, minimize the negative environmental impact of EV disposal and meet the governmental regulations associated with used EV batteries (International Energy Agency, 2019). Due to the relevance of the EV batteries' EoL management, a growing number of academics have published novel pieces of research about the EoL and circular economy of EV batteries.

DeRousseau *et al.* (2017), for instance, proposed a set of energy storage applications to extend the life of used electric vehicle batteries when they reach their end of life in the automotive industry. In this research, the authors discussed the economic feasibility of repurposing batteries by reviewing previous models and studies. The authors also highlighted the importance of evaluating the battery's State of Health (SOH) before the beginning to the second life use and the constant monitoring to ensure a sufficient capacity in the new application. The first possible application proposed by DeRousseau *et al.* (2017) was the use of batteries to peak shaves. In the energy industry context, peak shaving refers to the levelling out of peaks in electricity used by power consumers. Instead of installing new grid infrastructure, which demands a significant investment, EV batteries could be used to store electricity in times of low demand and use this electricity during peak times. Another option is the use of EV batteries for energy arbitrage. This means that when energy is cheap, for instance, during the night, the batteries can be charged, and when energy is more expensive, the stored electricity can be used. A third option proposed by DeRousseau *et al.* (2017) was the use of batteries for frequency regulations. When the electricity demand is higher than that generated, the missing energy needs to be supplied. In this case, battery EV batteries are a faster asset to supply this missing energy than other alternatives such as kinetic energy of a wind generator's rotors or thermal power plants. Finally, according to the authors, batteries could be used to support the generation of renewable sources of energy such as wind and solar. As wind and solar energy production are intermittent, EV batteries may be used to store energy in times of overgeneration and discharge energy during peak times (DeRousseau *et al.*, 2017).

Similarly, Olsson *et al.* (2018) did a qualitative research through interviews and workshops with stakeholders to explore how the battery value chain and business models may become more circular through recycling and second life use. The stakeholders that participated in the research were OEMs, energy storage suppliers for a second life, energy companies, recycling companies and government agencies. The study results suggested that it is economically viable to use EV li-ion batteries for second-life use and that they fit the storage requirements for a wide range of applications. Several business opportunities were also identified by Olsson *et al.* (2018). For instance, an electric vehicle OEM may sell their used LIBs for second life use instead of paying for their disposal. Moreover, energy storage providers may offer more environmentally friendly options, and recyclers may use their know-how in collecting and recycling valuable materials (Olsson *et al.*, 2018). However, there are also some barriers to using li-ion batteries for second life and recycling, which the author categorized as cognitive, organizational and technological. As Olsson *et al.* (2018) suggested, these barriers may be alleviated by collaborating among the different value chain actors and making the most out of the expertise of each of them. The main contribution of Olsson *et al.'s* (2018) paper is the conceptualization of four business models scenarios based on the level of customer value proposition and value network. The four business models proposed by Olsson *et al.* (2018) were: Linear model (Battery production and use in vehicle + currently practised recycling Model), Optimized recycling (Battery production and use in vehicles + state of the art recycling), Circular model I (Battery production and use in vehicle + repair and refurbishing for a second life use in a vehicle in the same or a new market + state of the art recycling) and Circular model II (Battery production and use in vehicle + repackaging and second life use in a different application + state of the art recycling) (See Figure 2.11).

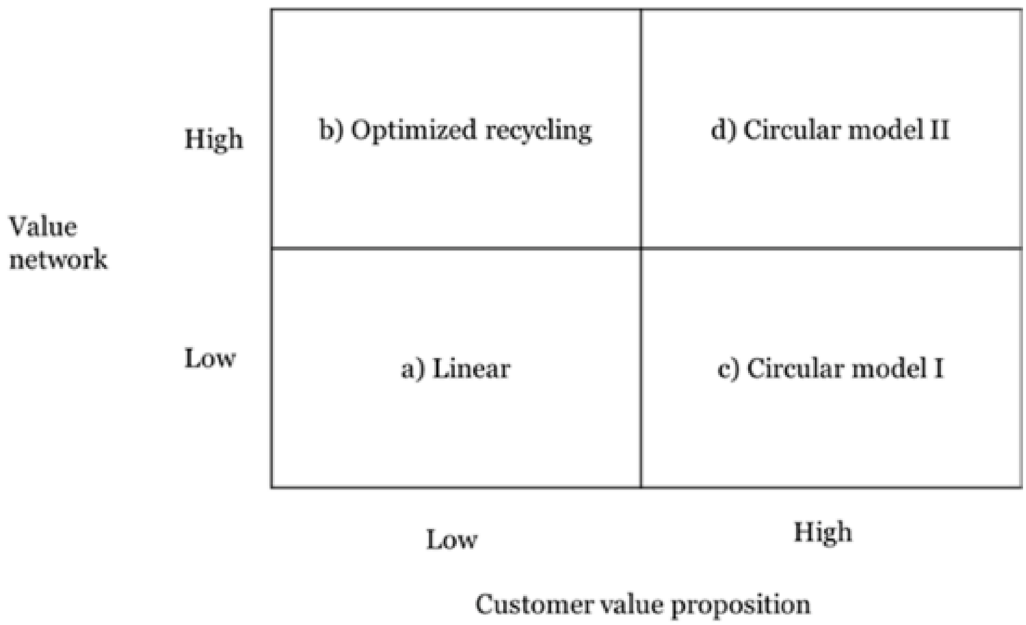


Figure 2.11. Four business model concepts (Olsson et al., 2018)

As the authors remarked, if OEMs were to collaborate with battery refurbish companies, second-life users and recyclers from the beginning, they would be able to make the transition from first life use to second life easier (Olsson *et al.*, 2018). By collaborating, companies may reduce costs and learn about the important benefits of adapting these batteries for a second life (Olsson *et al.*, 2018). As the authors conclude, looking for collaboration opportunities in the battery value chain is vital to developing new business models that beneficiate all the battery value chain actors.

Other authors have also studied the end-of-life opportunities according to the battery capacity using different approaches, such as mixed methods. For example, Canals Casals, Amante García, and Cremades (2017) conducted qualitative and quantitative research that is divided into four main parts. The first part discusses the relevance of the SOH measurement and estimation. As the authors suggest, car manufacturers have defined that batteries reach their EoL when they have 80% of their capacity (Canals Casals, Amante García and Cremades, 2017). However, as the authors suggest, car owners may not return their batteries when they reach those levels since the SOH of the battery is not immediately visible. The life span of batteries also depends on weather conditions and users' driving habits. After a thoughtful analysis, the authors proposed that the SOH of returned EV batteries follow a normal distribution centred on 80% with a 5th and 95th percentile at 70% and 90%, respectively (Canals Casals, Amante García and Cremades, 2017). The second part of the study is related to the different remanufacturing options to prepare batteries for their second life. The remanufacturing options discussed were direct reuse, module dismantle and cell dismantle. In the direct use, the SOH and characteristics of the battery are measured in the conditions that they arrive, and minimum adaptations are made for second life use. While the other options are module dismantle and cell dismantle, in which batteries are dismantled into modules or cells to regroup them for a new use. The third part of the study discussed several second life options depending on the SOH of returned batteries and the remanufactured process followed (Canals Casals, Amante García and Cremades, 2017). Figure 2.12 summarizes Canals Casals, Amante García and Cremades' (2017) proposed flow diagram that batteries may follow when reaching the EoL. According to Figure 2.12, batteries with SOH higher than 88% should be sent back to be used in EVs. Meanwhile, batteries that have between 75% and 88% can be used for stationary applications or other transport services that do not require high load levels (e.g., urban trucks, boats, and ferries at the entrance of ports). On the other hand, batteries with SOH lower than 75% should be dismantled into modules or cells (Canals Casals, Amante García and Cremades, 2017).

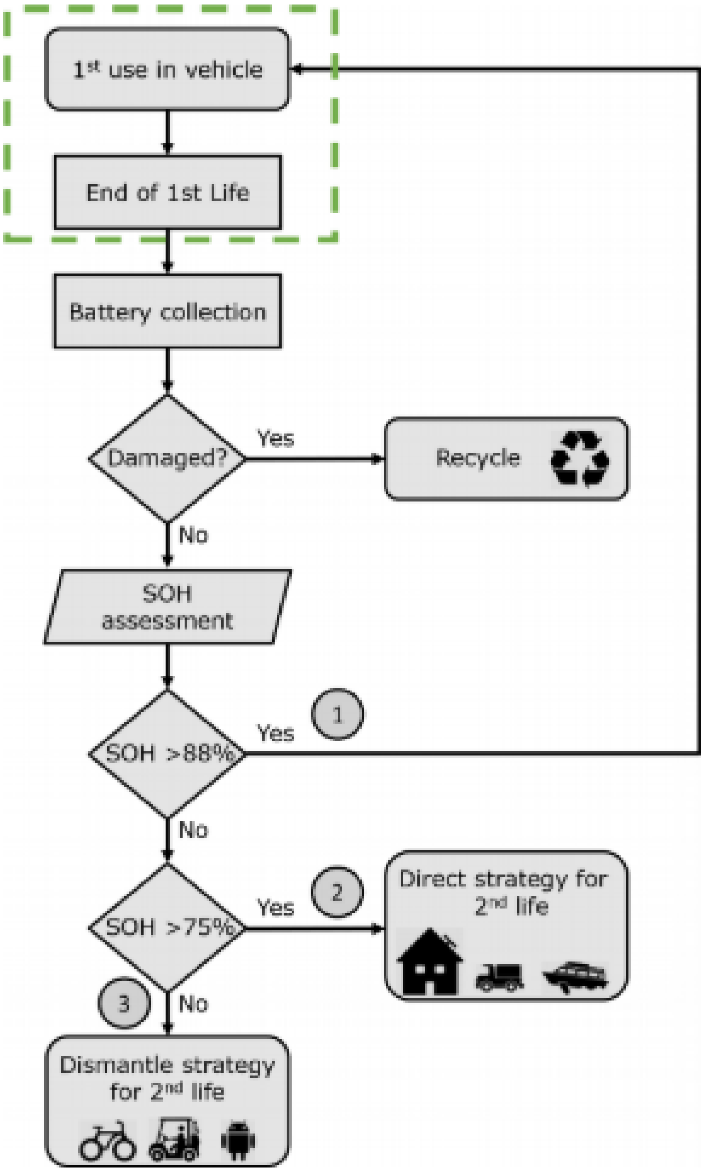


Figure 2.12. Decision making flow diagram for batteries at the end of its 1st life on EVs (Canals Casals, Amante García and Cremades, 2017)

Finally, in the last part of Canals Casals, Amante García and Cremades' (2017) study, the best location for a remanufacturing plant in Europe is calculated using the centre of mass equation. The variables used for the analysis were the number of sold EV, the distances around Europe, the main EV manufacturing locations and the countries' involvement with electricity grid decarbonisation. According to the results, Germany was chosen as an appropriate location to establish a remanufacturing plant.

There have been some attempts to address the study of the reverse management of EV batteries. Klör, Bräuer and Beverungen (2014) proposed an eight-step business model process for RL EVBs following the principal German regulations (Figure 2.13).

To create this high-level business model, the authors used as input the review of literature, legislations related to EV batteries and interviews with industry experts (Klör, Bräuer and Beverungen, 2014). The eight steps business model consisted of receipt and classification, inspection, decision making and disposition, specifying handling requirements, preparation of transportation, authority approval, transportation and delivery; and reprocessing (Klör, Bräuer and Beverungen, 2014).

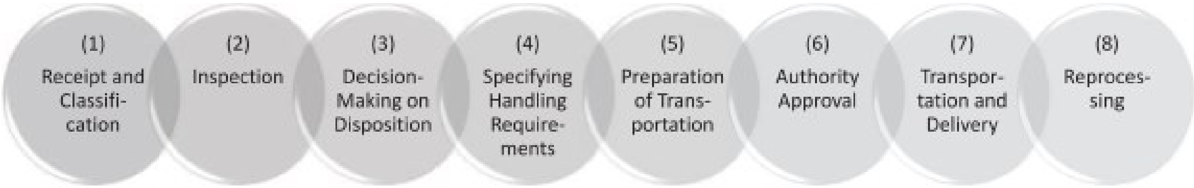


Figure 2.13. The high-level process for the reverse logistics of EVBs (Klor, Brauer and Beverungen, 2014)

In the first step, which is 'receipt and classification', a regular employee is in charge of receiving an EV from a customer to identify the type and specification of the EV battery received. After finishing the task, an electrical qualified employee is in charge of the following three steps. During the 'inspection' stage, the electrical employee should proceed with the battery removal and condition check that could fall into two states: damaged or undamaged. During the 'decision making and disposition', the electrical expert should decide if the battery should be recycled or reused. If the battery is damaged or undamaged, different handling requirements should be specified to have the batteries ready for the next step, 'preparation for transport', which should be conducted by the suggested carrier. If the battery is damaged, the 'authority approval' must take place to inform the transport carrier about the goods they are going to transport by sending a dangerous goods notification so the carrier can accept or decline. However, there is no need for authority approval when the battery is not damaged. Finally, the transportation and delivery and reprocessing steps are conducted.

2.7.3. EV batteries policies and regulations

As Winslow, Laux and Townsend (2018) suggest, waste management regulations are essential to protect humans' health and the environment since they provide guidelines about how hazardous and non-hazardous materials should be managed at their EoL. Moreover, regulations can promote the development of collection and recycling systems for some disposed materials. The legislation related to the end-of-life management of products has been based on Extended Producer responsibility (EPR) principle.

According to EPR, the producers of final goods are physically and financially responsible for the collection and appropriate treatment of the products at their end-of-life (Souza, 2018).

The rigorousness and scope of waste regulations vary depending on the country and local governments. In the case of Li-ion battery waste, there is no global regulation to this date. However, in some regions such as North America and Europe, the establishment of disposal bans and the development of collection systems are becoming more popular (Winslow, Laux and Townsend, 2018). Table 2.6 summarises some of the main LIB regulations and policies in place for different countries and regions.

Table 2.6. Summary of LIB regulations and policies in multiple countries with possible strategies to improve collection and recycling rates

Country	Description of regulations and policies in place	Target collection rates and recycling efficiencies (if applicable)	Advantages and possible strategies for improvement
United States	No collection or recycling is required on a federal level. Some states ban LIBs from disposal in landfills.	Collection rate: N/A	**Advantages:** An extensive voluntary collection system has been established and many domestic recycling companies are operating within the country or in Canada.
		Recycling efficiency: N/A	**Strategies:** LIBs could be classified as a universal waste, similar to lead acid and nickel cadmium batteries. This would encourage LIB recycling and discourage disposal to MSW landfills.
Canada (for the provinces of BC, MB, and QB)	Three provinces require manufacturers to have a collection system in place for waste LIBs.	Collection rate: Varies	**Advantages:** A collection system is required to be in place for these three provinces and collection rates have been established. Also, the recycling industry is fairly developed and is required to meet a target recovery efficiency.
		Recycling efficiency: 50%	**Strategies:** The other Canadian provinces could work with Call2Recycle to establish their own collection rates and target recycling rates.
European Union	Laws are in place regarding the collection and recycling of waste LIBs	Collection rate: 45% (2016)	**Advantages:** Target collection rates and recycling efficiencies have been clearly specified in the EU Battery Directive and member states are required to participate. The EU also has a highly developed LIB recycling infrastructure.
		Recycling efficiency: 50%	**Strategies:** Because the EU has significant experience with LIB recycling, they could lead in the development of more efficient processes.
China	Encourages EV manufacturers to establish their own LIB recycling infrastructure (not required).	Collection rate: N/A	**Advantages:** Many manufacturers in China have partnered with recycling companies to bridge the gap between collection and recycling.
		Recycling efficiency: N/A	**Strategies:** More strict regulations could be enforced to increase participation in the LIB collection and recycling sectors. The recycling industry should be further expanded to keep up with the expected increase in LIB manufacturing and consumption.
Japan	Encourages manufacturers to collect and recycle waste LIBs (not required).	Collection rate: N/A	**Advantages:** Japan has a well-established recycling infrastructure and LIB collection system.
		Recycling efficiency: 30%	**Strategies:** Laws related to LIB management are mostly voluntary, so more stringent regulations could be enforced to increase collection rates. The establishment of a country-wide target collection rate could be helpful.
Australia	No laws requiring the collection or recycling of LIBs.	Collection rate: N/A	**Advantages:** Collection systems are in place throughout the country.

The European Union uses the European List of Waste (LoW) to classify waste as hazardous or non-hazardous. The categories used in the LoW are absolute hazardous (AH), absolute non-hazardous (ANH), and mirror entry. The first two categories are classified without any previous assessment, while the latter requires an additional assessment to assign them to the AH or ANH categories. The lead-acid, Ni-Cd, and mercury-containing batteries are all classified as an AH waste (European Commission, 2015). However, li-ion batteries are considered in the group of other batteries and accumulators, making them an ANH waste (European Commission, 2015). However, this directive does not specify a specific target for automotive batteries. According to the European Commission, there is no collection target for automotive batteries because OEMs and 3PL are already obligated to take waste batteries back from final users to treat and recover material as stated in DIRECTIVE 2000/53/EC on end-of-life vehicles Articles 5, 6 and 7 (European Commission, 2020b). Moreover, Directive 2000/53/EC prohibits these products from ending in landfilling or being incinerated (European Commission, 2000). There are also financial incentives and penalties for infringements to ensure a good collection of automotive batteries. As the European Commission suggest, automotive and industrial batteries are collected by professionals due to their particular characteristics and economic value. For this reason, almost 100% of these batteries are collected (European Commission, 2000). According to the Directive 2000/53/EC in the site for treatment of end-of-life vehicles, there should be appropriate containers for storage of batteries filters and PCB/PCT-containing condensers (European Commission, 2000). The EU directive 2008/68/EC on the inland transport of dangerous goods also provides guidelines for the transportation of dangerous goods (European Commission, 2008).

On July 2023, the EU published the Regulation (EU) 2023/1542 on batteries and waste batteries. The new regulation defines requirements for sustainability, safety and information that apply to a wide range of batteries including electric vehicle batteries. The Regulation (EU) 2023/1542 (European Commission, 2023) applies to all manufacturers, producers, importers and distributors of batteries that operate in the EU market. ELV regulations and battery regulations such as Regulation (EU) 2023/1542 (European Commission, 2023) promote an environmentally friendly EoL management of EV batteries by defining responsibilities for the EoL management of EV batteries, the processes that need to be followed, and collection targets. The new regulation maintains the prohibition of waste battery landfilling and continues suggesting that all end-of-life batteries must collected by OEMs free of charge.

The new regulation also suggests that the components of batteries should contain a specific proportion of recycled material by 2031 and 2036 respectively:

The target by 2031 is: 16% cobalt, 85% lead, 6% lithium, 6% nickel

The target by 2036 is: 26% cobalt, 85% lead, 12% lithium, 15% nickel.

The new Regulation (EU) 2023/1542 of the European Parliament and of the Council concerning batteries and waste batteries (European Commission, 2023) mentions that batteries can be recycled, repurposed and remanufactured. To ensure compliance with the EU battery regulation (European Commission, 2023), EV and industrial batteries exceeding 2 kWh must have a digital battery passport by 2027. The battery passport should include pertinent data from the entire battery lifecycle, such as battery chemistry, capacity, performance, safety, cycle life, ecological footprint, and calendar data. The new EU battery and waste battery regulations set several requirements that cover the whole battery's life cycle and second life, including remanufacturing, reusing, and recycling. Hence, as a consequence of the new regulations, stakeholders like battery manufacturers and EV manufacturers have new obligations that must be fulfilled.

2.8. Summary of literature gap and research question

In sum, this chapter started by reviewing the literature related to sustainable supply chains and the relevance of addressing sustainability from a supply chain perspective. Then, the literature about the modelling approaches used in supply chain research is reviewed. The main types of simulation modelling techniques (i.e. system dynamics, DES) and the approaches of operational research interventions (i.e. expert and facilitated modes) were discussed. The facilitated modelling approach was identified as a suitable strategy to analyse complex problems or make strategic-level decisions, especially in cases where there is a lack of appropriate data for an objective analysis using simulation. Next, the literature on reverse supply chain design was critically reviewed. It was identified that there are several approaches to address the design of RSC issues, such as linear programming, non-linear programming and simulation. Several gaps were identified in the literature review on Reverse Supply Chain design. Firstly, most of the papers use complex mathematical model approaches (e.g. linear and non-linear programming) to address the RSC and CLSC design. Moreover, most of the reviewed models focus on mature industries and making the processes more efficient rather than making them more sustainable. A significant limitation of these modelling approaches is the difficulty for non-experts in building them and adapting them to reflect real industry contexts. In addition, despite some practical simulation models found in the literature, the models reviewed are limited to a quantitative evaluation without a thoughtful understanding of the industry context and design process. Also, most of the models studied only include manufacturers and recyclers in their reverse supply chain models and do not consider other key actors such as remanufacturers, refurbishing companies and second life clients and the relevance of the relationships between them to build successful and sustainable supply chains.

Finally, the electric vehicle battery industry was identified as an interesting context for this study for the following reasons:

- In 2023, almost 3.2 million electric vehicles were registered in Europe, up 20% from 2022. As the average EV battery lasts 10 years, the EoL supply chain of this component must be ready to accommodate the growing volumes of batteries that will approach end-of-life in the coming decades.In the automotive industry, minimising the batteries' raw material extraction and decreasing the environmental impact of these products is necessary.

Batteries and waste batteries regulations promote an environmentally friendly EoL management of EVs by defining responsibilities for the EoL management of EVs and EV batteries, the processes that need to be followed, and collection targets. Table 2.7 summarises the most important research gaps identified in the literature and how they are addressed in this research.

Table 2.7. Research gaps identified in the literature review (Author, 2024)

N°	Research gap	Addressed in this study
1	Most of the case studies that have used modelling approach, study existing supply chain with historical data using expert mode intervention approach.	Model a supply chain that is still developing, does not exist with limited historical data available using facilitated modelling approach.
2	Previous research on RSC design has been limited to the use of complex mathematical models which are difficult for non-experts to build and adapt to reflect real industry contexts. Most of the models focus on efficiency rather	This research uses a mix-methods approach that will combine qualitative and quantitative methods. Moreover, a facilitative modelling process in an industry context is used to create a simulation model that

	than sustainability. There is a lack of industry cases.	allows the main stakeholders to understand the problem situation better and assess potential improvement alternatives to make their RSC more sustainable.
3	The practical models found in the literature ignore the industry context and other factors that influence design decisions (e.g. suppliers' capabilities, legislations).	Through the qualitative analysis, this research considers the impact of the industry context and the drivers and barriers internal and external to the supply chain.
4	Most of the models studied include only manufacturers and recyclers, ignoring other key stakeholders and their relationships.	This research includes other relevant key actors in a reverse supply chain besides manufacturers and recyclers, such as remanufacturers, refurbishing companies and second life repurposing companies. Moreover, it discusses the relationships between key stakeholders to build successful and sustainable supply chains.

To bridge the gaps identified in the literature, the research questions guiding this research are the following:

- ***RQ1:*** *What are the requirements for designing a sustainable EoL RSC in an emerging sector?*
- ***RQ2:*** *How can an EoL RSC be designed to meet operational and sustainability objectives?*

3. Theoretical perspective

3.1. Overview

This chapter reviews the most common theories used in sustainable and RSC research which are: Agency theory, Stakeholder theory, Resource dependence theory, Resource based-view, Natural Resource-based view. Then, discuss how the theoretical perspective selected in this research has been used in previous literature and justifies the selection of the theoretical perspective used in this research.

3.2. Theories in sustainable supply chain management and Closed-Loop Supply chain

To contribute to the knowledge and apply it to a discipline, scholars need to design their research to provide an understanding of the practical problems of the field by using a theoretical basis (Simon, 1967). As Van de Ven (1989) suggests, a theory is practical because it helps advance the knowledge of a discipline, helps to ask relevant questions and enlightens the management profession. Kerlinger (1979) defines a theory as *"a set of interrelated constructs (variables), definitions, and propositions that presents a systematic view of phenomena by specifying relations among variables, with the purpose of explaining natural phenomena"* (p. 64).

According to Toubolic and Walker (2011) systematic literature review on theories in sustainable supply chain management, most of the academic papers on sustainable supply chain, Closed-Loop Supply Chain (CLSC) do not use a theoretical basis to guide their research (Touboulic and Walker, 2011). Only five relevant pieces of research were found in the literature that have used well-established theories to study concepts and relationships to contribute to academic knowledge. (see for examples: Masoumik *et al.*, 2014; Miemczyk, Howard and Johnsen, 2016; Ashby, 2018; Flygansvaer, Dahlstrom and Nygaard, 2018; Kalaitzi, Matopoulos and Clegg, 2019).

The theories chosen to be analysed in this research are Agency Theory, Stakeholder theory, Resource Dependence Theory (RDT), Resource-based View (RBV), and Natural Resource-based View (NRBV), which are some of the most popular approaches in the sustainable supply chain management domain (Touboulic and Walker, 2011).

The reasons to discuss these theories in this research among all the widely used theories in the sustainable supply chain management and CLSC fields are the following:

- Agency theory is used to describe the relationship between a party that delegates a work (principal) and the party that performs the work (agent) using the metaphor of a contract. This theory could be helpful in studying the relationship needed between the principal firm and its several agents in a reverse supply chain to make it sustainable.

- Stakeholder theory looks at how companies are influenced and pressured by institutions and other stakeholders. This theory could be helpful in identifying the main stakeholders in a reverse supply chain and institutions that have a voice and power to affect the dynamics of the reverse supply chain operations.

- RDT, RBV and NRBV focus on the resources that companies need to succeed. These theories could be helpful in identifying the resources that a firm needs and can obtain through its reverse supply chain partners.

3.2.1. Agency theory

Agency theory aims to describe the phenomena in which one party, which is called the principal, delegates work to another (the agent), who is the party that performs the work (Eisenhardt, 1989a). The agency theory is used to describe the relationship between the principal and the agent using the metaphor of a contract (Jensen and Meckling, 1976). As Eisenhardt (1989) suggests, when the principal aims to maximise the profit and there is self-interest, the agency theory can be used to determine the most efficient contract for the principal-agent relationship. The agency theory unit of analysis is the contract that defines the relationship between the principal and the agent. This theory aims to decide the most efficient contract to determine the relationship between the principal and the agent considering people, firms and information assumptions (Eisenhardt, 1989a). The agency theory has two main research streams: the positivist and principal-agent (Jensen, 1983). The positivist agency research has focused on studying situations where the principal and the agent have disputing goals and illustrate the governance dynamics that limit the self-orientated behaviour (Eisenhardt, 1989a). The positivist stream lays in the foundation that there are agency problems in organisational relationships, and there are also various contract alternatives for each agency problem. The principal agency theory focuses on the general view of the principal-agent relationship and more directly on the principal-agent contract. According to Harris & Raviv (1978), this theory can be applied to employer-employee, lawyer-client, buyer-supplier, and other agency relationships.

The principal-agent stream pays significant attention to assumptions, makes logical deductions and proves them using mathematical tools. Principal-agent research aims to identify the most efficient contract type between the principal and agent in a given context.

3.2.2. Stakeholder theory

According to Toubolic and Walker (2011) systematic literature review on theories in sustainable supply chain management, another popular theory used in the sustainable supply chain domain is stakeholder theory . Freeman (1984) was one of the first authors that proposed a stakeholder framework in his book “Strategic Management: A Stakeholder Approach”. To build the famous stakeholder approach, Freeman analysed several pieces of research that included corporate planning, system theory and corporate social responsibility. Freeman (1984) proposed the stakeholder theory to respond to the inefficacy of the existing management theories in the 80s. Such theories did not consider the business environment (e.g. international competition, industrial relationships, a globalised resource market, government pressures, changing consumer habits, environmental concerns, and advances in communication technology) (Laplume and Litz, 2008). According to Freeman (1984), a stakeholder is *“any group or individual who can affect or is affected by the achievement of the organisation's objectives” (p.46).* The unit of analysis for the stakeholder theory is the firm embedded in a network of stakeholders. The stakeholder theory proposed by Freeman (1984) suggests that there are internal and external parties (e.g. employees, customers, suppliers, communities, governmental bodies, political groups, competitors) (Mitchell and Wood, 1997) that can affect or be affected by firms’ practices. As Sarkis et al. (2011) argue, companies produce externalities that affect other stakeholders. Because of these externalities, stakeholders increase their pressure on organisations. Stakeholder theory helps to understand what parties have a voice in an organisation and who benefits from those decisions (Crane and Ruebottom, 2012).

3.2.3. Resource dependence theory

The resource dependence theory (RDT) is another influential theory in organisational and strategic management that has been widely applied in sustainable supply chain management research. Some of the most important contributors to the theory are Pfeffer and Salancik (1978), who published their popular book “The External Control of Organisations: A Resource Dependence Perspective” in 1978. According to Pfeffer & Salancik (1978), the RDT suggests that organisations cannot be self-sufficient; on the contrary, they depend on other organisations’ resources to succeed. The resource dependence theory proposes that entities that control organisations' essential resources acquire power that differentiates them from other environmental parties (Pfeffer, 1981). The resource dependence theory suggests that firms that lack specific resources should develop relationships with other organisations to acquire the needed resources and succeed in the long term, instead of taking advantage of other companies to gain short term benefits (Sarkis, Zhu and Lai, 2011). For instance, if an organisation decided to collaborate with another firm to develop innovation, it would be essential to identify the missing resources of one company and complement them with another company's resources (Cricelli, Greco and Grimaldi, 2021). According to Sarkis *et al.* (2011), inter-organisational innovation collaboration can only succeed when organisations fully understand and integrate other companies' knowledge and technologies. Cohen & Levinthal (1990) name such capability as absorptive capacity. Zobel (2017) broke down the concept of absorptive capacity into three main components: recognition, assimilation, and exploitation. According to Zobel (2017), recognition refers to the capability to identify and assess the external needed resources; assimilation allows companies to analyse and assimilate the knowledge from the external organisation; and finally, exploitation is the capacity to apply the interiorised external knowledge into the organisation (Zobel, 2017). From a supply chain perspective, RDT indicates that a company depend on other firms and should combine its resources through collaboration to reach high performance (Sarkis, Zhu and Lai, 2011).

3.2.4. Resource-based View

The resource-based view (RBV) is the most popular theory used in the sustainable supply chain management domain according to Toubolic and Walker (2011) systematic literature review on theories in sustainable supply chain management,. Barney (1991)suggests that a firm can gain a competitive advantage by using its valuable, rare, inimitable and non-substitutable tangible and intangible resources. Firms' resources do not only include their physical assets; they also include companies' capabilities, brands, processes, information and knowledge that allow a company to develop strategies to gain a sustainable competitive advantage (Barney, 1991; Daft, 1998). A company's resources do not only consider the resources within the firm; they also can include the resources that are out of the firm boundaries and can be found, for instance, in an extended supply chain (Barney, 1991; Teece, Pisano and Shuen, 1997). In the supply chain context, the RBV concept can explain firms' participation in networks to gain competitiveness by expanding internal resources (Barney, 1991). One of the most significant paradigm shifts during the last decades in management is that the business competition is no longer firm vs firm; it is supply chain vs supply chain (Lambert, Cooper and Pagh, 1998; Lambert and Cooper, 2000). Acquiring the knowledge and capabilities in a supply chain, for instance, to be green, are resources that can be studied using the resource-based view (Wang, Lai and Shi, 2011). Previous research has also used resource-based view theory to understand how reverse logistics implementation could bring a sustainable competitive advantage by improving environmental and economic performance (Huang and Yang, 2014).

3.2.5. Natural resource-based view

Hart (1995) proposed the Natural resource-based view (NRBV) theory which is based on and expands the traditional RBV. According to Hart (1995), the RBV presented by Barney (1991) that considered an internally based competitive approach was insufficient since it did not consider external relationships' impact. The NRBV suggests that a firm can obtain a competitive advantage by recognising the challenges imposed by their organisation's natural and social environment and developing business capabilities to react to them (Hart, 1995). The NRBV involves the development of internal capabilities but also considers stakeholder and institutional considerations as external aspects of the strategy (Hart, 1995). According to NRBV, the unit of analysis is the firm, as a bundle of resources and its internal and external processes to manage these resources. As Touboulic and Walker (2011) suggest, sustainability pressures can allow companies to differentiate from their competitors and increase their power.

NRBV theory postulates that there are three interconnected organisational strategies:

- Pollution prevention strategy aims to prevent waste and emissions along with the operations rather than at the end, resulting in lower costs, increased efficiency, and higher profitability for the firm (Hart and Dowell, 2011).

- Product stewardship strategy considers the environmental performance of a product during the whole lifecycle (i.e. design to disposal). This strategy helps to identify significant changes in the supply chain configuration to close the loop of operation (Hart, 1995).

- The sustainable development strategy seeks to do less harm to the environment and looks for ways to produce in a way that can be maintained over time. Moreover, sustainable development is not limited to the environmental aspect but also includes the economic and social aspects (Hart and Dowell, 2011).

3.3. Use of Natural Resource-Based View theory in sustainable supply chain and closed-loop supply chain

According to Toubolic and Walker (2011) systematic literature review on theories in sustainable supply chain management the NRBV theory has been used as a theoretical lens in the sustainable supply chain (SSC) and closed-loop supply chain domain. Some authors have made significant contributions to the knowledge by developing frameworks for sustainable supply chain design (SSCD) (Masoumik *et al.*, 2014); studying the strategic resources needed to develop successfully closed-loop supply chains (Miemczyk, Howard and Johnsen, 2016); and investigating how CLSC can be successfully developed to address environmental sustainability (Ashby, 2018).

Masoumik *et al.* (2014) proposed a conceptual framework (See Figure 3.1) that presents a SSCs design components that include SSC practices, processes and structures, aligning them with the different NRBV environmental strategies and how they add value to shareholders. The authors used NRBV to understand how the environmental strategies proposed by this theory could provide value to shareholders in the long term and, consequently, a competitive advantage for the firm. According to the NRBV, the environmental strategies of pollution prevention, clean technology, and product stewardship can provide value to shareholders through risk and cost reduction, innovation and repositioning, and reputation and legitimacy, respectively. Aligned with the NRBV environmental strategies and applying a configuration approach, the authors proposed three SSC configurations; efficient SSC adopting pollution prevention strategy, innovative SSC adopting clean technology strategy, and reputed SSC adopting product stewardship strategy (Masoumik *et al.*, 2014). According to Masoumik *et al.* (2014), companies cannot apply all the SSC practices due to resource constraints. Hence, they should choose the type of value they desire to achieve, identify the correspondent environmental strategy and, based on that strategy, select the most strategic practice to design a sustainable supply chain.

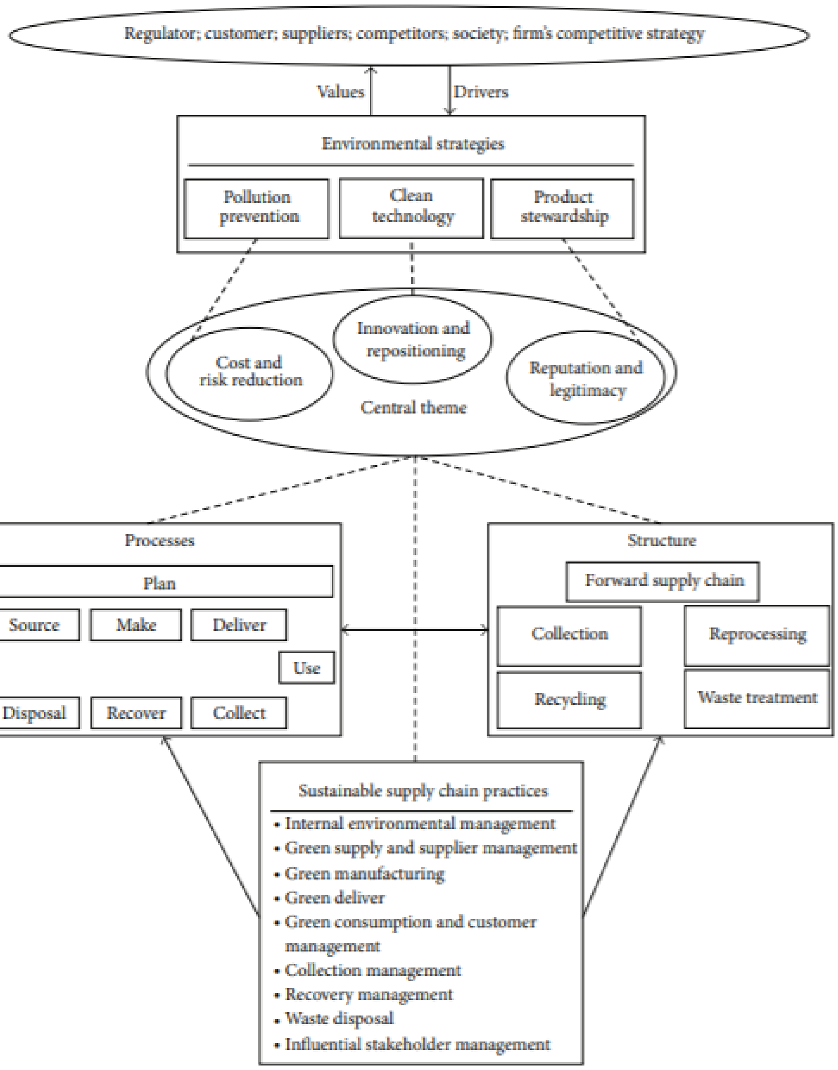


Figure 3.1. A conceptual framework for designing a sustainable supply chain (Masoumik et al. 2014)

As the authors suggest, the efficient SSC configurations follow the pollution prevention strategy to prevent waste and emissions in operations (Masoumik *et al.*, 2014). This type of configuration looks to reduce cost and risk. Some practices to meet this environmental strategy are green supply and purchasing and green process design (Masoumik *et al.*, 2014). These processes should be designed cost-effectively, resulting in standardised and procedural methods. Innovative SSCs are aligned with a clean technology strategy that looks to develop the competencies to innovate in the future. An example of SSC practices that fit the innovative SSC configuration is product eco-design and clean energy and technology (Masoumik *et al.*, 2014). According to the authors, the processes for these practices should be designed flexibly and innovatively to allow rapid competencies development. Reputable SSCs follow the product stewardship environmental strategy that aims to include the stakeholders' perspectives in the business processes to achieve reputation and legitimacy (Masoumik *et al.*, 2014). Some of the practices of reputable SSC include collaboration with suppliers and customers and the participation of key stakeholders. As the authors suggest, the reputable SSC processes should be designed to allow collaboration with essential stakeholders (Masoumik *et al.*, 2014).

Miemczyk, Howard and Johnsen (2016) also presented a novel piece of papers that shifts the focus of CLSC research from pure logistics problems to strategic resources and capabilities through the NRBV and Dynamic Capabilities (DC) lenses. The authors used NRBV and DC to study the relevant resources in technology, knowledge, and relationships needed to develop a successful CLSC (Miemczyk, Howard and Johnsen, 2016). Moreover, they highlighted the importance of DC in renewing strategic resources and facing changes in the business environment. The authors chose the textile and carpet manufacturing industries to show how successful CLSCs can be explained using the NRBV and DC theory lenses and understand the main challenges of adapting their capabilities to achieve a closed-loop business model. According to the authors, traditional theoretical perspectives related to core competencies and RBV suggest there is a dilemma for firms that desire to collaborate with other companies to support sustainability when they need to keep core knowledge to maintain market advantage (Miemczyk, Howard and Johnsen, 2016). In contrast, Hart’s (1995) NRBV highlights the dynamic relationships between external companies and stakeholders and the need to share core knowledge. In comparison to traditional RBV, NRBV pays more attention to the access to external resources found beyond the firm’s boundaries; however, there are limited pieces of research that have used NRBV to study CLSC (Sarkis, Zhu and Lai, 2011).

The few pieces of paper that have used NRBV as theory lenses in the CLSC context have focused more on measuring sustainability performance than on the role of capabilities for collaborative supply chain design (Grosvold, Hoejmose and Roehrich, 2014). For this reason, Miemczyk, Howard and Johnsen (2016) chose NRBV as a relevant theory to rethink the relationships and boundaries of firms that aim to transition toward CLSCs. As the authors suggest, understanding the role of DC to extend, restructure and update the resource base, including various supply chain members, is necessary to develop the theory linking NRBV and CLSCM. For this reason, Miemczyk, Howard and Johnsen (2016) proposed a framework that shows the factors involved in transitioning toward CLSCs (See Figure 3.2). The authors used NRBV to represent how pollution prevention strategy, product stewardship, and sustainable development are embedded and follow a dependency path. The conceptual framework shows how pollution prevention capabilities are needed to support product stewardship. The proposed framework highlights the relevance of “Dynamic supply chain execution” and “Collaborative internal/external development”, which are supported by drivers and antecedents and lead to CLSC implementation. The framework highlights that not only the focal firm is responsible for the CLSC transition; instead, all the core actors need to cooperate and build relationships to succeed.

Figure 3.2. An initial conceptual framework for transitioning towards CLSCs (Miemczyk, Howard and Johnsen, 2016)

Ashby (2018) presented a case study of a UK clothing company to study how a CLSC can successfully address environmental sustainability. As part of her research, the author used NRBV as a theoretical framework to understand the processes that companies need to follow to create a CLSC and the impact resources and relationships have in this process. As Ashby, Leat and Hudson-Smith (2012) suggest, sustainable supply chain research has focused on tangible processes. Only a few papers have recognised the relevance of building relationships within CLSCs. Therefore, as the author suggested, prior to their research, there was a need to address this gap by applying a theoretical framework that addressed tangible and intangible resources of CLSC to achieve sustainability (Ashby, 2018). The NRBV theory provides essential insights into understanding CLSC development. According to Ashby (2018), NRBV is a theory that acknowledges the relevance of strategic tangible and intangible resources in firms and supply chains. This theory is also helpful to understand how the relationships between suppliers and the resources generated by these relationships add value to supply chains.

Following Hart's (1995) three environmental strategies, namely pollution prevention, product stewardship and sustainability, Ashby (2018) discussed how the CLSC components are aligned and presented in the literature to justify the use of NRBV in her research. Table 3.1 summarises how these strategies are interconnected and follow a sequence where each strategy builds on the prior one. According to Ashby (2018), pollution prevention is the strategy that the literature on NRBV has focused on more. This strategy is linked to the continuous improvement capability and looks to prevent pollution most effectively by minimising waste and emissions. Following the NRBV sequence, firms pass from internal pollution prevention to product stewardship. As Sarkis (1995) suggests, product stewardship strategy aims to minimise the environmental impact throughout a product lifecycle. Therefore, this strategy pays attention to product design and materials and encourages recycling, remanufacturing, and reuse (Wong *et al.*, 2012). According to Table 3.1, product stewardship expands the environmental perspective from a firm to the entire supply chain, including stakeholders and suppliers. For that reason, the product stewardship strategy promotes integration and cooperation with the different supply chain stakeholders (Ashby, 2018). At this stage, the focal firm starts integrating stakeholder interests and cooperating and collaborating with them to reduce the environmental impact of products throughout the product lifecycle. Recent literature has showcased how product stewardship and supply chain relationships can lead to better environmental outcomes (Grekova *et al.*, 2014). Table 3.1 highlights the importance of a shared vision as an essential resource to achieve sustainability by considering the whole product lifecycle from a long-term and proactive perspective. According to Ashby (2018), the latter strategy aligns with the CLSC concept that suggests that to succeed, firms need to account for the environmental impact of their operation and demand a proactive and integrated supply chain.

Table 3.1. The natural resource-based view of the firm (Ashby, 2018)

Strategic capability	Environmental driving force	Key resource	Competitive advantage
Pollution prevention	Minimise emissions and waste	Continuous improvement	Lower costs
Product stewardship	Minimise lifecycle cost of products	Stakeholder integration	Pre-empt competitors
Sustainability	Minimise environmental burden of firm growth and development	Shared vision	Future position

Source: Hart (1995)

Figure 3.3 shows the research framework used by Ashby (2018) that includes the main environmental and NRBV concepts identified in the literature. The author used this framework to study how companies can progress and move from one NRBV strategy capability to another to develop a successful and coordinated CLSC. The framework represents the resources obtained from suppliers' relationships and how these contribute to success in each capability stage. Ashby's (2018) study findings were discussed against the NRBV framework, and the author highlighted the resources and supplier relationships' role in achieving successful CLSC.

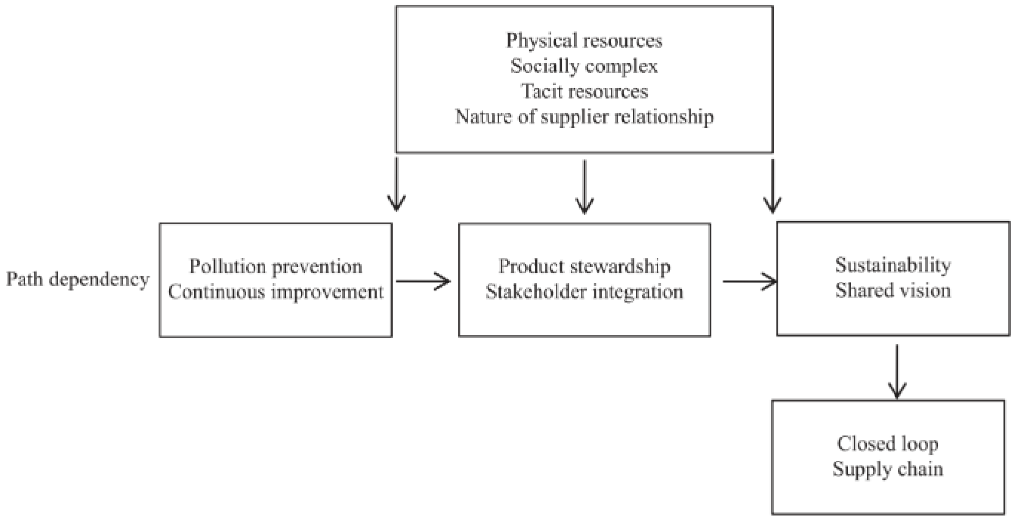


Figure 3.3. Developing closed loop supply chains for environmental sustainability research framework (Ashby, 2018)

3.4. Conclusion of the chapter

In sum, this chapter discussed the relevance of using a theoretical basis to understand practical problems and advance the knowledge of disciplines. Five of the most important theories used in sustainable supply chain management and closed-loop supply chain domain found in Toubolic and Walker (2011) systematic literature review on theories in sustainable supply chain management were analysed. The theories were chosen due to their wide application in related fields and their relevance to the study of EoL reverse supply chains. The chapter's objective was to identify the most suitable theories to study the main factors influencing an EoL reverse supply chain implementation in a developing industry.

NRBV was chosen as the theoretical lens for this research for the following reasons:

- An essential part of EoL reverse supply chain design is identifying the strategic tangible and intangible resources and capabilities needed to succeed. NRBV has proven to be a useful theory for studying the resources and capabilities needed in the fields of sustainable supply chains and closed-loop supply chains.

- The EOL reverse supply chains involve multiple stakeholders that may be found within their supply chain network (e.g., recyclers and manufacturers) and outside the supply chain (e.g., government). This study looks to understand the role of the suppliers' and stakeholders' relationships in achieving a sustainable EoL reverse supply chain. For this reason, NRBV is a suitable theory for identifying the impact of suppliers and stakeholders and how these can build relationships to develop successful EoL reverse supply chains.

- Supply chain design elements such as practices, processes and structures can be aligned with the NRBV environmental strategies to decide on the most suitable supply chain strategy to follow and add value to shareholders. Therefore, NRBV can be used in this research to align the reverse supply chain design elements with the desired supply chain strategy and add value through reverse supply operations.

- Hart's (1995) NRBV theory could be used as a framework to understand how the different environmental strategies proposed by this theory (e.g. pollution prevention, product stewardship, and sustainability) could provide value to shareholders through the development of an EoL reverse supply chain.

- From the operational perspective, pollution prevention, which is one of the three NRBV strategies, can guide the design of efficient reverse supply chains that minimise the costs and risks of operations.

- Product stewardship strategy looks to minimise the environmental impact of products throughout the product lifecycle. This strategy involves the participation of different entities across the supply chain, including stakeholders and suppliers. Therefore, a product stewardship strategy could be used to study the various EoL stakeholders and suppliers' involvement in a reverse supply chain. Moreover, this strategy could help justify the cooperation and collaboration strategies across an EoL product reverse supply chain.

4. Conceptual Framework

4.1. Overview

Developing a conceptual framework is an important part of the research process. As Ravitch and Riggan (2016) suggest, conceptual frameworks help researchers structure and inform their studies; ensure that the topic, research questions and methods are aligned; and allow the researcher to integrate new findings, future research paths, and literature throughout the study. Given that the current literature that addresses sustainable supply chain and RSC has not used much theoretical basis in their research (Touboulic and Walker, 2011), this research proposes the use of NRBV to support the conceptual framework of this study. The NRBV theory and its three path dependency strategies (i.e. pollution prevention, product stewardship and sustainability development) were used to develop the conceptual framework of this research that aims to answer the following research questions.

- ***RQ1:*** *What are the requirements for designing a sustainable EoL RSC in an emerging sector?*
- ***RQ2:*** *How can an EoL RSC be designed to meet operational and sustainability objectives?*

To answer the research questions, it is critical first to understand the most important factors that influence a reverse supply chain development. Then, the current reverse supply chain design elements are studied. Finally, the alternatives to make this reverse supply chain design sustainable over time are explored.

Hence, this chapter presents a conceptual framework influenced by the NRBV theory to structure and guide this research. The proposed general framework is based on three main constructs: Drivers and barriers to the implementation of environmental strategies, Reverse supply chain design and Sustainable Reverse supply chain. These constructs are aligned with the NRBV's three path dependency strategies: Pollution prevention, product stewardship, and sustainability development. After developing the framework, a concise description and justification of the framework and the influence of each of the NRBV strategies in the research constructs are presented.

4.2. The initial conceptual framework built on NRBV

First, a general framework is proposed for an industry with a need to develop a sustainable EoL reverse supply chain to meet the different industry and environmental challenges. To create the general framework of this research, academic journals and news related to the EV industry and EV batteries were reviewed. The automotive industry has a mature supply chain with thousands of components suppliers and production plants worldwide. The EoL supply chain of the internal combustion engine (ICE) vehicles is also mature with a well-structured network of dealers, authorised treatment facilities, recyclers, remanufacturers, and other supply chain partners. However, during the last years, the electrification of the automotive industry is expected to cause significant disruption to car manufacturers' supply chain.

Electric vehicle batteries are the most critical component of electric vehicles because they account for one-third of the vehicle's cost and are highly relevant for EV development and adoption. Since EV batteries typically last between 8 to 10 years, the EoL supply chain of this component needs to be prepared to handle the increasing volumes of batteries that are going to reach their end-of-life in the following decades.

As Hart and Dowell (2011) suggest, sustainability development strategies look for alternatives to do less harm to the environment and to produce in a way that can be maintained in the long term. Moreover, according to Elkington (1998), sustainability consists of social, economic, and environmental pillars which constitute the triple bottom line (TBL). Implementing reverse supply chains is one of the most critical industry sustainability strategies and contributes to the development of sustainable operations (Kleindorfer, Singhal and Van Wassenhove, 2005).

The EV battery industry is a developing industry that needs to ensure its sustainability. Some of the drivers that are encouraging the development of reverse supply chains for EV batteries are the finite critical raw material supply (International Energy Agency, 2018; Moores, 2018), the negative environmental impact of EV battery production and disposal (Winslow, Laux and Townsend, 2018; International Energy Agency, 2019) and governmental regulations associated with used EV batteries (Winslow, Laux and Townsend, 2018; International Energy Agency, 2019). Several barriers that affect the EV reverse supply chain implementation have also been identified, such as the early development stage of suppliers, capacity, a major investment for EoL management facilities, and the labour-intensive nature of activities. Therefore, EV manufacturers need to build sustainable EoL reverse supply chains on time to address future industry challenges.

Some EV manufacturers like Nissan, Honda, Toyota and Volkswagen have started paying attention to the relevance of an EV battery reverse supply chain implementation. These companies are acquiring new resources and developing new EoL capabilities in-house or externally through their supply chain partners. For instance, some of these EV manufacturers have started adopting different EoL strategies through recycling and reusing batteries and components for second-life purposes (see for examples, Nissan Insider, 2016; Honda, 2019; Toyota, 2019; Volkswagen, 2019; Umicore, 2020). American, European, and Asian countries have already started developing a reverse supply chain for EV batteries; meanwhile, the reverse supply chain for EV batteries in the UK is still in a developing stage (WMG, 2020).

Prior literature has suggested that developing relationships has helped supply chain partners achieve sustainable performance and transition toward circular supply chains (Sudusinghe and Seuring, 2022). In addition, the NRBV theory recognises the role of relationships to minimise the environmental impact of products during their whole lifecycle through acquiring resources and capabilities from supply chain partners (Hart, 1995). However, limited literature has studied how companies can design their reverse supply chains to make them sustainable and the role of business relationships in meeting that purpose from an industry perspective using well-established theoretical lenses. Moreover, few pieces of research have studied in-depth the drivers and barriers for the reverse supply chain implementation in a developing industry such as the EV battery industry.

One of the theories used in the sustainable and reverse supply chain context is the NRBV. According to Hart's (1995) NRBV, firms can obtain a competitive advantage by acknowledging the challenges of a firm's natural and social environment and developing capabilities to react to them. Hart (1995) proposed an NRBV framework composed of three interconnected organisational strategies: pollution prevention, product stewardship and sustainable development.

As seen in Hart and Dowell (2011) and Mena *et al.*(2014)., most of the research that has applied NRBV has focused on the pollution prevention strategy and how to reduce costs by reducing emissions and waste, while the product stewardship and sustainable development strategy has received less attention.. In this research, all of Hart's (1995) NRBV path dependency strategies (i.e. pollution prevention, product stewardship and sustainability development) are used. These strategies are used to identify the factors that influence a reverse supply chain implementation, the necessary reverse supply chain design components and the alternatives to make this reverse supply chain design sustainable over time.

Therefore, taking in consideration the research gaps and EV industry context , the general framework is made of three constructs: Drivers and barriers for implementing environmental strategies, EoL Reverse supply chain elements and Sustainable Reverse supply chain design. These constructs are connected, considering the influence of previous literature (Miemczyk, Howard and Johnsen, 2016; Ashby, 2018). The proposed framework aligns with Hart's (1995) NRBV sequential environmental strategies: pollution prevention, product stewardship, and sustainable development (See Figure 4.1).

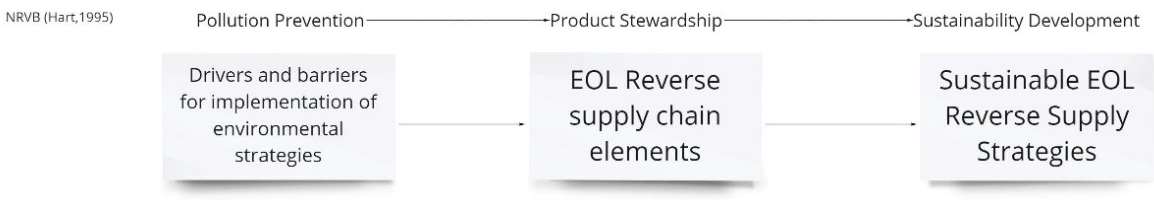


Figure 4.1. The general framework (Author, 2024)

Following the general framework structure, the initial conceptual framework is developed and shown in Figure 4.2. A concise description and justification of the framework, and the influence of each of the NRBV strategies in the research constructs are explained in the following subsections.

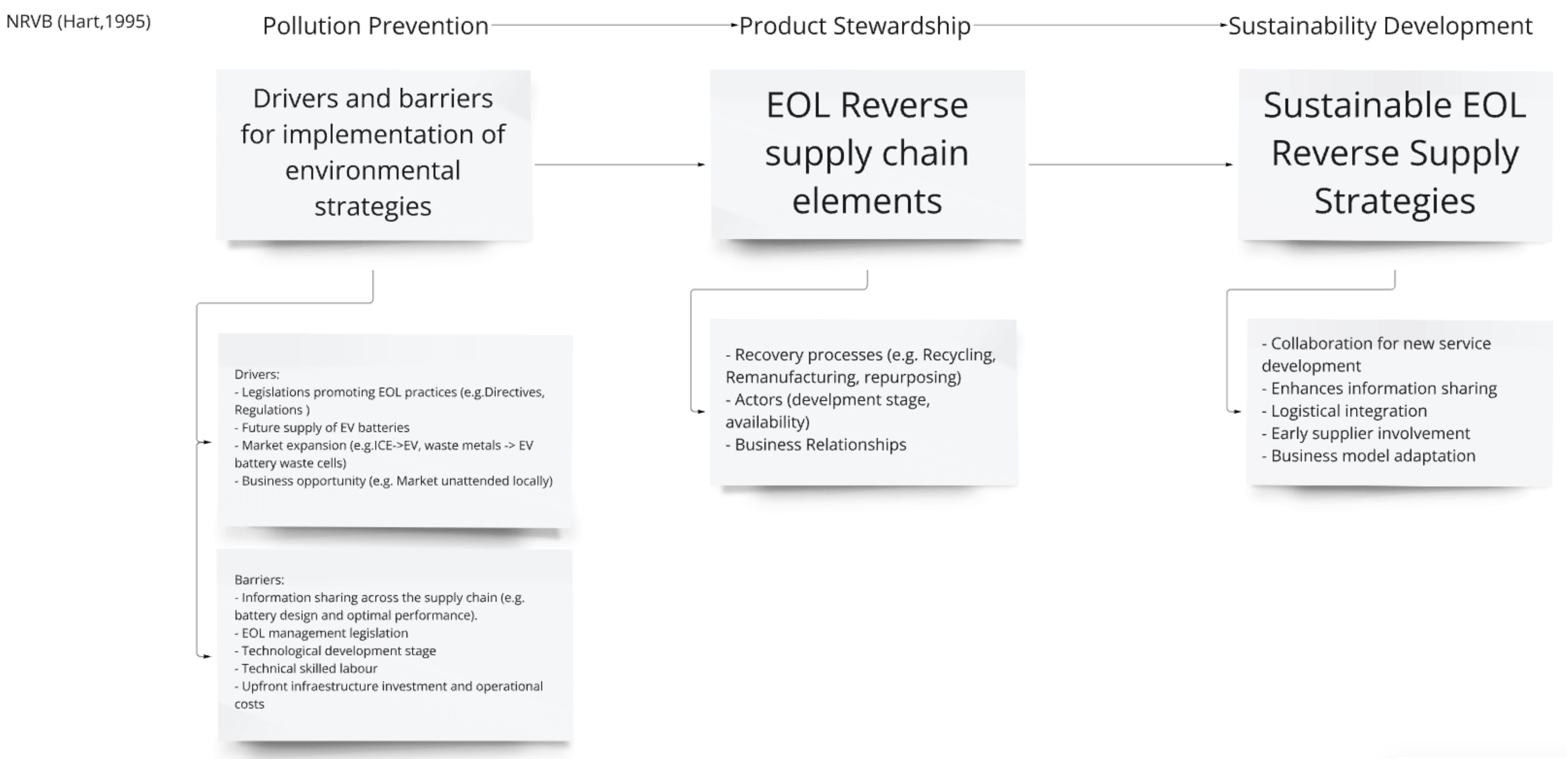


Figure 4.2. The initial conceptual framework (Author, 2024)

4.3. Drivers and barriers to implementing environmental strategies and their link with pollution prevention

The supply chain design decisions that companies make depend on the context they are. Hence, before discussing how companies can design reverse supply chains that can be sustainable over time, it is essential to identify the main factors that influence its development. The industry context encourages companies to adopt reverse supply chain strategies, but it also imposes some limitations on its development (Miemczyk, Howard and Johnsen, 2016; Kazemi, Modak and Govindan, 2019). In this research, the drivers and barriers to implementing environmental strategies such as reverse supply chain are studied to determine the components of an EoL reverse supply chain configuration and how to make it sustainable over time. In this context, drivers refer to the motivational factors that lead companies to do a certain activity. While the barriers are the impediments that disrupt the adoption of green activities.

According to Hart (1995), pollution prevention is a strategy that aims to continuously reduce, change and prevent waste and emission throughout the operations rather than at the end of the pipe, resulting in significant savings, efficient operations, and higher profitability for the firm (Hart, 1995). Vachon and Klassen (2006) suggest that pollution prevention strategies respond to environmental issues. In this research, the pollution prevention principles are used to identify the context where reverse supply chains are built. This context is going to be studied through the identification of the drivers and barriers to implementing environmental strategies that constitute the environment where reverse supply chains are implemented.

Several authors such as Govindan and Bouzon (2018); Govindan and Hasanagic (2018); and Narimissa, Kangarani-Farahani and Molla-Alizadeh-Zavardehi (2020) have studied the different drivers and barriers for the implementation of environmental strategies and have proposed a classification for them. These authors identified several drivers and classified them into clusters based on their similarities. The list of the drivers and barriers, their correspondent clusters and classification used in this research have been collected from previous literature (Govindan and Bouzon, 2018; Govindan and Hasanagic, 2018; Narimissa, Kangarani-Farahani and Molla-Alizadeh-Zavardehi, 2020) (See Figure 4.3)

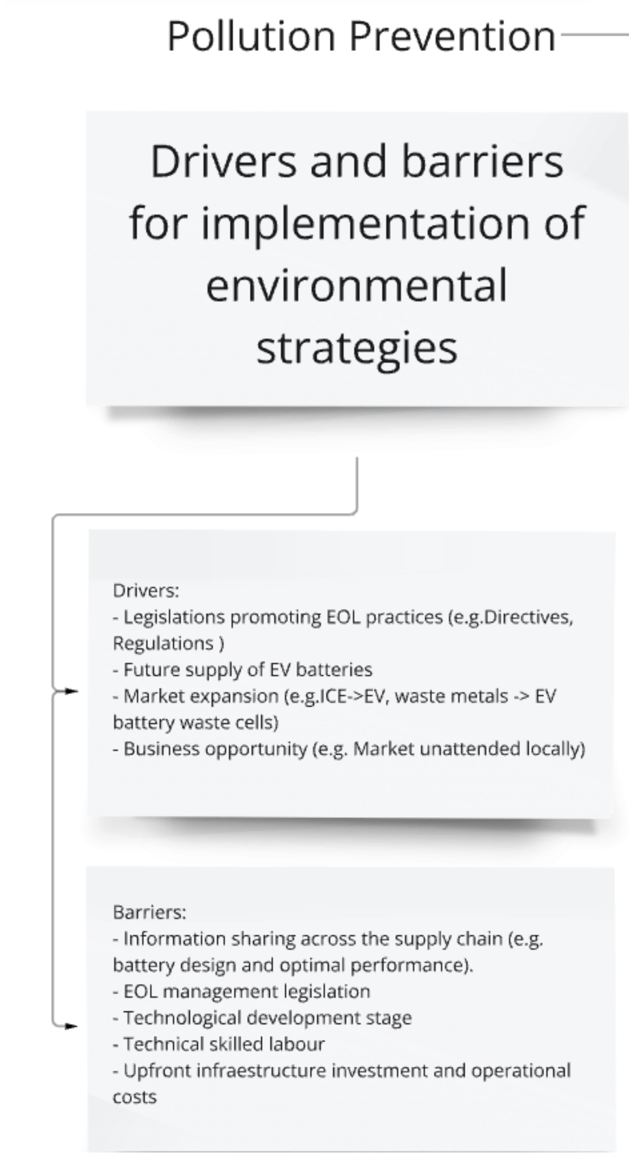


Figure 4.3. Drivers and barriers for implementation of environmental strategies construct (Author,2024)

4.3.1. Drivers

Govindan and Bouzon (2018); Govindan and Hasanagic (2018) and Narimissa, Kangarani-Farahani and Molla-Alizadeh-Zavardehi (2020) proposed frameworks to categorize the drivers for the RSC implementation. The most common driver categories are summarised below:

- **Policy:** This category includes changes in regulations and legislation concerning product recover and EoL management.
- **Management:** this category includes issues related to employee satisfaction, support from human resources, and the integration of departments in the context of RL practice.

- **Market and competition:** this category includes factors such as customer happiness, competitive advantage potential, green market concerns, and competitive pressures.
- **Technology and infrastructure:** this category includes the factors that drive information technology, accessibility of eco-design and design for 'X' procedures and recovery technologies.
- **Economy:** this category includes financial and economic drivers.
- **Knowledge:** this category includes internal resources within firms such as information flows and RL awareness.
- **Social:** this category includes societal pressures, such as higher public awareness of environmental conservation and the demand on companies to act responsibly.

According to the literature, one of the drivers for implementing environmental strategies is the nature of the raw material supply. It is well known that there is a problem with the availability of non-renewable resources (e.g. oil, gas) (Ponsioen, Vieira and Goedkoop, 2014) and the natural scarcity of some raw materials such as rare-earth elements (REEs) used for the production of high technology devices (Jowitt *et al.*, 2018). In the automotive industry, the growing demand and sales of EVs will imply a higher demand for EV batteries. This situation is expected to cause a rapid rise in the extraction of raw materials used in EV batteries, which poses a risk for the future EV supply chains (International Energy Agency, 2018). According to the latest BloombergNEF Electric Vehicle Outlook (2024), lithium-ion batteries are used in two-thirds of electric vehicle batteries. Lithium-ion batteries. Two of the main lithium-ion chemistries used in lithium-ion batteries are Nickel Manganese Cobalt (NMC), Nickel Cobalt Aluminium (NCA) (International Energy Agency, 2018; Moores, 2018). The main materials used in NMC and NCA batteries are lithium, cobalt, nickel and graphite, which are becoming scarce (Costa *et al.*, 2021). The low availability of resources requires firms to make changes in their existing supply chains, rethink and adapt their environmental strategies to minimise the use of scarce resources and reduce emissions (Chaabane, Ramudhin and Paquet, 2012). In this context, implementing pollution prevention strategies that minimise the use of scarce resources plays an emerging role (Fleischmann *et al.*, 2004; Srivastava, 2007).

Another driver for implementing environmental strategies related to raw material nature is waste production. Depending on the nature of the raw material used for manufacturing products, the resulting waste may negatively impact the environment.

When waste is disposed into the landfill, anaerobic decomposition takes place. As the water reaches the landfill, it extracts the chemicals producing organic acids (Renou et al., 2008; Kjeldsen et al., 2010). Moreover, according to Li et al. (2009), landfill leachate may transport pollutants even outside the landfill. In the case of lithium-ion batteries, , the main leachable metals are lithium, cobalt and nickel. These elements may be found inside the battery's cathode, which is protected by a case; however, as Winslow, Laux and Townsend (2018) suggest, when the case is damaged or broken, the inorganic elements inside the cathodes may be exposed (Winslow, Laux and Townsend, 2018). When lithium-ion battery pollutants are not treated appropriately, there is a risk that these could get out of the landfill and cause adverse effects on humans and the environment (Dubey, Townsend and Solo-gabriele, 2010). Lithium-ion waste does not only contaminate landfills. It can also contaminate water supplies when uncontrolled disposed, like in open dumps. Hence, it is crucial to design EoL reverse supply chains that minimise the pollution that products' waste may generate.

Another important driver for the implementation of environmental strategies is legislation. Winslow, Laux and Townsend (2018) suggest that waste management regulations and policies are vital to protect humans' health and the environment since they provide the necessary guidelines to manage and process materials when they reach their EoL. Furthermore, regulations foster the development of collection techniques and recycling facilities for some waste components (Winslow, Laux and Townsend, 2018). Countries and local governments are responsible for defining the scope and rigour of waste regulations. In the case of EoL lithium-ion batteries, there is no global regulation to this date (Zeng, Li and Liu, 2015; Winslow, Laux and Townsend, 2018). Some regions, such as North America and Europe, are leading the lithium-ion batteries regulatory agenda by establishing disposal bans and fomenting the development of collection systems (Winslow, Laux and Townsend, 2018). The European Union battery Directive 2006/66/EC on batteries and waste batteries for instance prohibits the disposal and incineration of all types of batteries, including lithium-ion batteries, delimits manufacturers' responsibilities and sets recycling targets (European Commission, 2020b). In the specific case of li-ion batteries, the EU Battery Directive establishes target collection rates of 65% by 2025 for all portable waste batteries (European Commission, 2020b). Article 8 in the EU battery Directive 2006/66/EC proposes the expected recycled content in industrial batteries, electric vehicle batteries and automotive batteries. From 2027, EV batteries that contain cobalt, lead, lithium, or nickel should start showing technical documentation that demonstrate the recycled material content (European Commission, 2020b). By 2035, the recycled material of these EV batteries should be no less 20% of cobalt, 12% of Nickel, and 10% of Lithium (European Commission, 2020b). Hence, legislations set the products EoL management scenario for companies and encourage the development of pollution prevention strategies in industries.

Another driver for the development of environmental strategies related to the legislation is the extended product responsibility. The obligations of companies to comply with the legislation will depend on their level of responsibility for managing the waste. The legislation related to the end-of-life management of products has been based on the Extended Producer responsibility (EPR) principle. According to EPR, the producers of final goods are physically and financially responsible for the collection and appropriate treatment of the products at their end-of-life (Souza, 2018). According to Article 47 of the EU battery Directive 2006/66/EC, all battery producers are required to collect, transport, treat and recycle all waste batteries (European Commission, 2020b). Article 49 refers to automotive batteries, industrial batteries and EV batteries in particular and suggests that all these types of batteries that have been placed in the market need to be collected free of charge from end users (European Commission, 2020b). According to Directive 2000/53/EC on end-of-life vehicles (ELVs), vehicle manufacturers that place the vehicles in the market have the physical and financial responsibility to take back EoL vehicles and their components. EV batteries are part of EVs; therefore, EV manufacturers must apply the corresponding measures to recover, reuse, recycle, remanufacture and dispose of its components (European Commission, 2020a). According to the EPR principle the responsibility remains with the original vehicle manufacturer when reuse occurs after remanufacturing or repairing batteries to be used for the same purpose, but it is transferred to the new producer when second-life applications for a different purpose are presented (Souza, 2018; European Commission, 2020a). Hence, EPR is another important mechanism that assigns companies the responsibility to adopt pollution prevention strategies by themselves or through specialised partners to make their supply chains more sustainable.

4.3.2. Barriers

Similarly, Govindan and Bouzon (2018); Govindan and Hasanagic (2018) and Narimissa, Kangarani-Farahani and Molla-Alizadeh-Zavardehi (2020) have proposed frameworks to categorize the barriers for the RSC implementation Some of the most common barrier categories are presented below:

- **Technology and infrastructure:** this category includes the barriers related to information technology, technical skills and infrastructure limitations.
- **Economy:** this category includes financial and economic barriers.

- **Knowledge:** this category refers to the dissemination of knowledge and the level of awareness in companies.
- **Policy:** this category includes issues on regulations and legislation related to product takeback and RL.
- **Market and competition:** this category includes issues related to competitive advantage reasons and recovery market.
- **Management:** this category includes issues related to the position of managers regarding environmental concerns and the contrasting importance of environmental initiatives in relation to other activities.

The literature suggests that the technological development stage is a critical obstacle to implementing EoL strategies. Recovering, recycling, repurposing, and remanufacturing EV lithium-ion batteries are complex activities from a technical perspective. EV Lithium-ion battery formulation, cell design, and combination in modules and battery packs differ significantly (Ramoni and Zhang, 2013). EV li-ion batteries are made up of a mixture of small components glued within the battery packs (Malinauskaite, Anguilano and Rivera, 2021). There are three main lithium-ion recycling technologies. Pyrometallurgical, hydrometallurgical, and Direct recycling processes (Chen *et al.*, 2019). The pyrometallurgical process involves the extraction of metals from lithium-ion batteries by applying heat, melting, and separating components. The Hydrometallurgical process uses aqueous solutions to leach in acids and bases that are later concentrated and purified. And direct recycling harvests and recovers active materials of lithium-ion batteries maintaining the original compound structure (Chen *et al.*, 2019). A fourth recycling technology that is still being researched is called bio-hydrometallurgical process involving bio-leaching for metal extraction (Swain, 2017). The first two methods, Pyrometallurgical processes, Hydrometallurgical processes, are well established. However, only recently they have recently started to operate at industrial scales (Chen *et al.*, 2019). In the case of direct recycling, it has only been applied in a lab environment and at a pilot scale (Chen *et al.*, 2019). Consequently, the activities to recover the value from EV lithium-ion batteries components and materials involve high energy-intensive processes that are difficult to standardise and are still in an early development stage.

Another important barrier to the EoL management of products, especially for the remanufacturing and repurposing of high technology products, is the need for highly specialised and skilled labour. Discarded lithium-ion batteries can cause explosions since they keep some electrical power (Zeng, Li and Liu, 2015). In addition, manipulating these types of batteries may cause serious hazards. Lithium-ion battery manipulation can cause side reactions and create a hazard risk (Lisbona and Snee, 2011). Besides toxic material, lithium-ion batteries contain highly flammable organic elements such as electrolytes. Organic electrolytes in lithium-ion batteries are considered to cause the primary toxicity and flammability risks because they may explode or catch fire.

Moreover, if the electrolyte is exposed to water, it may release toxic gases (Heelan *et al.*, 2016). Also, there may be possible reactions at high temperatures between the organic solutions and the electrode surface (Zeng, Li and Liu, 2015). Heat generation and thermal management should be controlled to ensure safe operations. Therefore, it is essential that OEMs and 3PL providers be aware of the potential risks associated with the handling of batteries, make sure to train their workers to be highly skilled and specially trained, and follow careful procedures to minimise the risks.

Another barrier to the implementation of EoL EV batteries strategies is related to the high investment in plants and technological development and operational costs. As Malinauskaite, Anguilano and Rivera (2021) suggest, from an economic perspective, repurposing and second-life applications for EV batteries may be profitable depending on the revenues from the sales of repurposed and refurbished batteries, costs associated with disassembly, remanufacturing, refurbishing or repurposing. In order to do these activities, it is necessary to have bespoke facilities which demand a major upfront investment. For instance, the lithium-ion battery recycling process demands a high upfront investment to set up the mechanical and hydrometallurgical technology (Rohr *et al.*, 2017). In the recycling process, the operational labour cost is relatively low compared to the remanufacturing and repurposing processes due to the high level of automation. In the case of remanufacturing and repurposing EoL EV lithium-ion batteries, besides the infrastructure investment, the main cost drivers are operational. According to Zhu *et al.* (2021) study on the Perspective End-of-life or second-life options for retired electric vehicle batteries , some of the most critical operational costs are battery collection costs, SOH testing, and the cost associated with breaking down and repacking cells, modules and battery packs. The logistic costs associated with battery collection depend on the geographical distance between the collection area and the repurposing/remanufacturing facility. In countries like the US, the transportation cost may represent between 30% and 50% of the total remanufacturing/repurposing cost (Standridge and Hasan, 2015). According to the National Renewable Energy Laboratory (NREL), the labour cost represents a great deal of the total testing and refurbishing cost. Most of the cost is associated with the breakdown of the battery modules (Zhu et al., 2021).

4.4. Reverse supply chain design and its link with product stewardship

As Hart (1995) suggests, pollution prevention focuses on new capability building in production and operations. In contrast, product stewardship strategy considers the environmental impact of a product during the whole lifecycle (i.e. raw material access to disposal/recovery). Product stewardship expands the environmental perspective from a firm to the entire supply chain, including stakeholders and suppliers. Therefore, the product stewardship strategy promotes integration and cooperation with the different supply chain stakeholders (Ashby, 2018). Product stewardship considers the stakeholder's perspective and helps identify improvement opportunities in the supply chain configuration to close the loop (Hart and Dowell, 2011). As Sarkis (1995) suggests, a product stewardship strategy aims to minimise the environmental impact throughout a product lifecycle. Therefore, this strategy pays attention to product design and materials and encourages recycling, remanufacturing, and reuse (Wong *et al.*, 2012). This strategy involves the participation of different entities across the supply chain, including stakeholders and suppliers.

Therefore, a product stewardship strategy could be used in this research to study the various EoL processes and actors involved in a reverse supply chain. Moreover, this strategy could help justify the relationship decisions across an EoL product reverse supply chain. Implementing RSC is one of the many environmental strategies companies can take to go one step further from pollution prevention strategies. The development of RSCs is aligned to Hart's (1995) product stewardship strategy since RSCs are created to recover products that are not used anymore from customers and reprocess them to recover part of their value or dispose them (Guide Jr. and Van Wassenhove, 2002; Gupta, 2012).

Reverse supply chain design elements such as practices, processes and structures can be aligned with Hart's (1995) product stewardship to decide on the most suitable reverse supply chain strategy to follow and add value to shareholders. Therefore, product stewardship principles can be used in this research to align the reverse supply chain design elements with the product stewardship strategy and add value through reverse supply operations.

As was identified in the literature, reverse supply chain design research has focused on quantitative approaches and modelling. As suggested by Gobbi (2011) only a limited number of studies consider the design and implementation of the reverse chain from a more holistic perspective, providing business guidelines. In this research, the RSC design is going to be studied from a holistic perspective, taking into consideration the main RSC processes, actors involved, and relationships (See Figure 4.4).

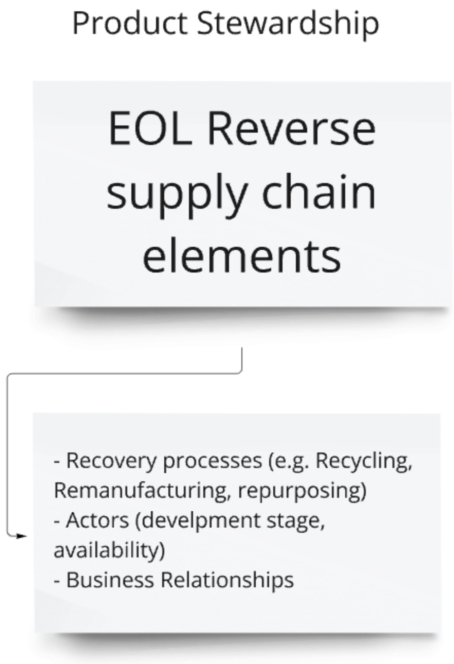


Figure 4.4. EoL Reverse supply chain elements construct (Author, 2024)

4.4.1. RSC processes and actors

An RSC is a network of companies that perform activities to recover products that are not used by customers and reprocess them to recover part of their value or dispose of them (Guide Jr. and Van Wassenhove, 2002; Gupta, 2012). Hence, RSCs can receive different types of returns. According to Jayant, Gupta and Garg (2012), there are four types of returns: End-of-Life Returns, End-of-Use Returns, Commercial Returns, and Reusable Components. End-of-Life Returns refer to products taken back from the market when they reach their EoL to avoid environmental harm. These types of products normally must be collected from the market to comply with the local or national waste and EoL products regulations and directives. The second type of return is the End-of-Use Returns. These types of returns are the products that the customers return after they have finished using them (Jayant, Gupta and Garg, 2012). End-of-use returns can be traded in the aftermarket or remanufactured. The third type of return is the commercial return. Commercial returns occur when the client receives the wrong or faulty product or returns a product during the warranty period or for product recalls (Jayant, Gupta and Garg, 2012). The final type of return is the reusable components. These returns happen when the main product is consumed or used. The component return is not part of the product commercialised but usually carries the main product in reusable containers (e.g. returnable glass bottles, returnable cartridges) (Jayant, Gupta and Garg, 2012). This research focuses on the reverse supply chain for EoL returns of products since it is expected to be the most predominant stream for EV batteries.

A reverse supply chain is constituted by the actors that perform the necessary activities to recover products that are not used anymore from customers and reprocess them to recover part of their value or dispose of them (Guide Jr. and Van Wassenhove, 2002; Gupta, 2012). Depending on the type of industry and products, types of reverse supply chains have different processes and actors.. This research requires a thorough understanding of the major reverse supply chain process to identify the main activities and actors in the supply chain studied, in this case RSC for EV batteries. According to Fleischmann, Ronald and Dekker (2000), there are five key types of business processes that take place in a reverse supply chain: (1) Collection/Product acquisition, (2) Inspection/Separation, (3) Recovery, (4) Re-distribution and sales, (5) Disposal

- **Collection/Product acquisition**

This process involves all the activities related to the physical collection of products from the market and movement to a different location point for additional treatment (Fleischmann, Ronald and Dekker, 2000; Krikke, le Blanc and van de Velde, 2004). Sometimes the product acquisition can be made by a buy-back strategy. The arrangements and collection activities can be done by the manufacturer, retailer or through a third-party logistics service provider and arranged with the customer (Krikke, le Blanc and van de Velde, 2004).

- **Inspection/ Sorting**

Involves all the activities to determine if a product or any component can still be used or recovered. Inspection and sorting involve separating the flow of used products according to their characteristics to choose the most suitable recovery option in the reverse supply chain or disposal alternative. The inspection process may involve different activities such as disassembling, shredding, testing, sorting and storing (Fleischmann, Ronald and Dekker, 2000). The sorting will depend on the results of the inspection process (Krikke, le Blanc and van de Velde, 2004).

- **Recovering**:

This process involves transforming a used product into a usable product, component or material again. This transformation can be done, for instance, through recycling, repairing, and remanufacturing. The recovery process also involves other activities such as cleaning, replacing, and reassembly (Krikke, le Blanc and van de Velde, 2004).

When discussing the main recovery strategies, several authors refer to the Circular Economy concept. According to Kirchherr, Reike and Hekkert (2017), *“A circular economy describes an economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and be- yond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations.”* (Kirchherr, Reike and Hekkert, 2017, p.224)

Depending on the authors that number of circular economy strategies that help to reduce the use of natural resources and minimise waste production may vary from four to nine. One of the most famous circular economy frameworks is the one proposed by Potting *et al.* (2017) . Potting *et al.* (2017) proposed a framework with nine strategies organised in order of priority according to their level of circularity (Figure 4.5). The nine strategies are grouped into three main categories. The first group with the highest level of circularity is “Smarter product use and manufacture”. The strategies in this group try to make more efficient use of manufacturing resources and, instead of extending the product's life, allow more people to use it. The next group of strategies is “Extend the lifespan of the product and its parts”. It involves strategies such as reuse, refurbishing and remanufacturing that help expand a product's life. The last group of strategies is “Useful application of material” that includes recycling of valuable product material an incineration which is the strategy with the lowest level of circularity.

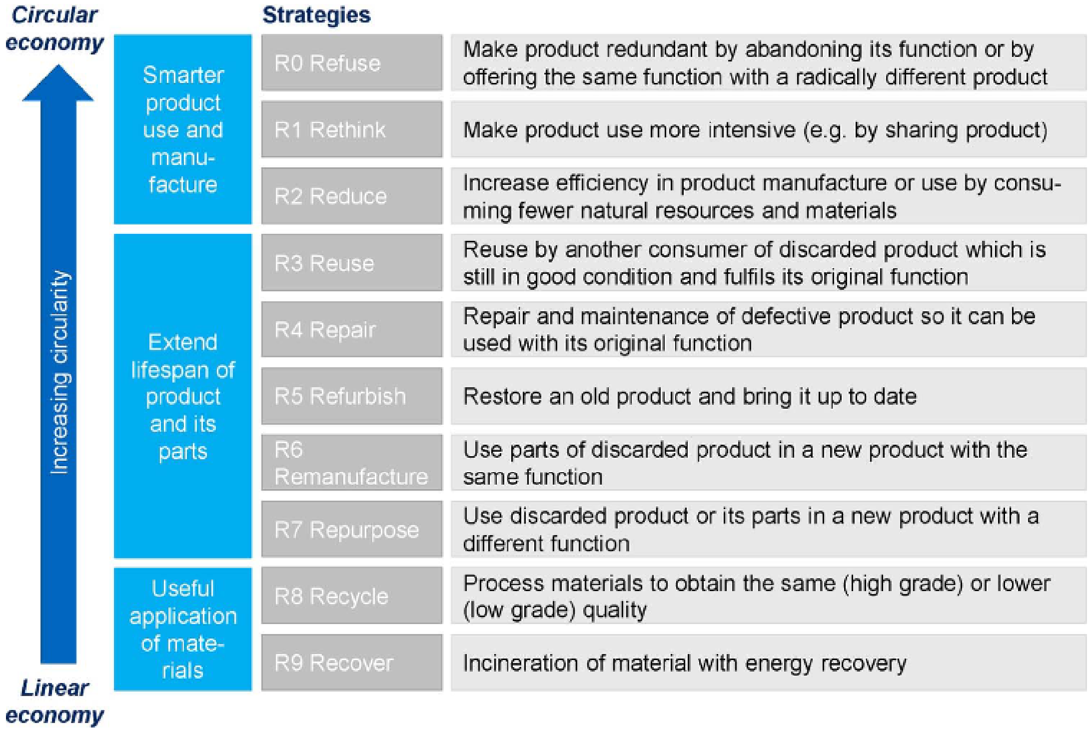


Figure 4.5. The 9R framework (Potting et al. 2017, p.5)

- **Re-Distribution and Sales:**

This process includes the distribution and sales of recovered products and materials. It is vital to follow recovery processes that assure the quality of the product and transmit that message to potential clients to convince them that the products are worth buying. New markets may need to be developed for the recovered products and materials. Consequently, a new supply chain and re-distribution channels need to be created (Krikke, le Blanc and van de Velde, 2004). The activities in this stage involve the development of new sales strategies, transportation and warehousing for the recovered products and materials (Fleischmann, Ronald and Dekker, 2000).

- **Disposal**

This is the process used when a product cannot be reused or recovered due to technical or economic reasons. A product is usually disposed of when, at the inspection, it is identified that the product cannot be recovered because it is too expensive or destructive. Products can also be disposed of when they do not have market potential, such as when outdated technology is used. However, companies also need to be aware of the legislation around the EoL management of products since they may prohibit the disposal of such products (Fleischmann, Ronald and Dekker, 2000).

4.4.2. RSC processes and actors in the EV battery industry

According to previous studies in the EV battery sector conducted by Canals Casals, Amante García and Cremades (2017); and Chen *et al.*, (2019) recycling, remanufacturing, and repurposing are some of the most popular recovery alternatives in the reverse supply chain of EV batteries. The decision about the best EoL alternative depends on the battery's design characteristics, the quality of the EoL product and state of health (SOH) of the battery and cells. Remanufacturing and repurposing are the preferred options, from a circular economy perspective, that maximise the recovered value from EV batteries and minimise the energy consumption after first-life treatment (Canals Casals, Amante García and Cremades, 2017; Chen *et al.*, 2019). However, remanufacturing is the most exigent alternative in terms of quality and SOH requirements. The second desirable option after remanufacturing is repurposing of EV batteries for second life in a different industry. Recycling is the least favourite option from a circular economy perspective because of the reduced benefits, loss of material and energy consumption of the recycling processes. Nevertheless, recycling is still better than EoL EV batteries' disposal. Through recycling the valuable material of batteries can return to the EV battery supply chain reducing the extraction of raw material (Chen *et al.*, 2019).

- **Remanufacturing**

Remanufacturing is the process by which a product can be rebuilt and its components repaired and replaced to use the whole battery pack in its original automotive application (Chen *et al.*, 2019). The remanufacturing strategy includes diagnosing the battery modules and cells, replacing or repairing damaged cells and modules, and reassembling all the components into a new battery pack (Chen *et al.*, 2019).

Remanufacturing is the EoL alternative with the highest level of circularity for battery packs when their SOH is sufficient for EV use. According to the US Advanced Battery Consortium (USABC) standard only batteries with a higher capacity than 80% can be used in an EV. EV batteries with a lower SOH than 80% do not have enough energy and capacity to be used for automotive applications (DeRousseau *et al.*, 2017). When inspecting a battery pack, it could be possible that only a few cells do not meet the SOH requirements, but that does not mean that the whole battery should be discarded because it would imply wasting valuable components. Instead, the cells and modules can be repaired or replaced to use the remanufactured batteries in an EV (Chen *et al.*, 2019). A study made by Foster *et al.* (2014) suggested that using remanufacturing batteries saves approximately 40% of the cost of producing a new Li-ion battery.

However, remanufacturing also poses different challenges. There is a wide variety of battery pack designs with different sizes, chemistries and formats (cylindric, prismatic and pouch), which adds complexity to the remanufacturing process due to the lack of standardisation (Engel, Hertzke and Siccardo, 2019). By 2015 nearly 250 new EV models will be introduced to the market, produced with batteries from more than 15 manufacturers. (Engel, Hertzke and Siccardo, 2019)

One company that has been offering remanufacturing services for EV battery packs along with repairing and refurbishing has been Spiers New Technologies (SNT). SNT has operations in North America, Europe and China, offering its services to leading EV manufacturers (SNT, 2022). Another company in the EV remanufacturing business is Global Battery Solutions. Global Battery Solutions offers lifecycle management services for batteries and electronics. Some of the services for electric vehicle batteries are repairing, remanufacturing, repurposing and recycling depending on the state of the lithium-ion battery pack (Global Battery Solutions, 2022). Global Battery Solutions suggest that the cost of replacing a li-ion battery could be reduced by more than 70% by using remanufactured batteries (Chen *et al.*, 2019).

- **Repurposing**

Based on DeRousseau *et al.* (2017) study, repurposing is the second preferred EOL option for EV batteries after remanufacturing. The repurposing process extends the lifetime of the battery pack in a different industry or application, e.g. energy storage. This alternative is recommended for EV batteries that are in good condition and still have high capacity left, but it is not enough to continue using them for EV applications that normally require a capacity above 80% (DeRousseau *et al.*, 2017). Repurposing EV batteries does not involve only replacing and repairing battery cells and modules. Repurposing also involves reconfiguring such elements into new modules and packs and a new battery management system to adapt them to the new applications needs.

In contrast to remanufacturing, repurposing EV batteries poses different challenges. Some of the challenges are the accuracy of the quality grading of the repurposed battery pack, difficulty to disassembly battery packs with different designs, reconfiguration costs that should compete with new batteries and transfer of liability (Chen *et al.*, 2019). EV batteries were created for and to be used in EVs. Moreover, EV manufacturers are responsible for collecting and treating these batteries at their EOL. However, the risks and legal responsibilities of using these batteries in a different application are not clearly defined in the legislations (DeRousseau *et al.*, 2017).

The decision to repurpose EV batteries should pass through careful economic analysis. Repurposing batteries involve testing, grading and repacking, which are significantly expensive and could make the decision to repurpose not economically viable (Chen *et al.*, 2019). As Chen *et al.* (2019) suggest these costs may be reduced by using more advanced technology, e.g. Sharing BMS information to measure the batteries' SOH and grading. Repurposed batteries can be used for different applications such as peak shaving, backup energy storage, renewable energy storage, and EV charging (Canals Casals, Amante García and Cremades, 2017; Olsson *et al.*, 2018).

Depending on the power and expected lifetime of the EOL EV batteries, these can be used in different second-life applications (Olsson *et al.*, 2018). Nissan for instance, is giving a second life to its EV li-ion batteries for their xStorage portfolio of products. Nissan EOL li-ion batteries are used as home storage units in the xStorage products. These batteries are used as storage units, which you can be controlled by users, deciding how and when the energy is used. Nissan builds a partnership with Eaton, a power management innovation company, to develop and create xStorage, a scalable energy storage system for homes and businesses (Nissan, 2022). General Motors has also been looking for repurposing alternatives for their Chevrolet Volt batteries. For one of the repurposing applications, GM worked with Empower Energies, a renewable energy services platform. They use the used Chevrolet batteries, solar arrays, and wind turbines to provide energy to GM enterprise data centre in Michigan (General Motors, 2015).

- **Recycling**

Recycling is the third and last EOL option that can be used for EV batteries. The recycling option can accept batteries with all SOH levels. However, according to Harper *et al*. (2019) recycling is more expensive than remanufacturing and repurposing, and it is the process that losses more valuable battery material. Recycling has been successfully applied for lead-acid batteries. However, lithium-ion batteries are more complicated and pose different challenges. Lithium-ion batteries have more materials than lead-acid battery packs, which makes them more difficult to separate. There are three main lithium-ion recycling technologies: Pyrometallurgical processes, Hydrometallurgical processes, and Direct recycling processes (Chen *et al.*, 2019). The first process consist of the extraction of metals from lithium-ion battery by applying heat, melting, and separating components. The Hydrometallurgical process uses aqueous solutions to leach in acids and bases that are later concentrated and purified. While, Direct recycling directly harvests and recovers active materials of lithium-ion batteries maintaining the original compound structure (Chen *et al.*, 2019). Even though recycling can be applied to EOL batteries with any SOH level, it should not be the first option for battery packs because of the loss of capacity. Sending EOL EV battery packs directly for recycling would imply the loss of their remaining capacity when they could still be remanufactured and repurposed (Ramoni and Zhang, 2013).

Two of the largest recyclers in Europe are Umicore and SNAM (Société Nouvelle d'Affinage des Métaux) which have been working together with the most important EV manufacturers. Umicore is a Belgium-based global materials technology and recycling group. Since 2006, Umicore has provided recycling services for lithium-Ion, lithium polymer and Nickel Metal Hydride batteries (NiMH) for diverse applications, including electric cars (Umicore, 2020b). On the other hand, SNAM is a French-based company that recycles Nickel-Cadmium, Nickel-Metal-Hydride and Lithium-Ion from portable batteries (e.g. mobiles, computers) and industrial batteries (e.g. trains, hybrid and electril vehicles, handling equipment) (SNAM, 2020).

Figure 4.6. shows the main processes and actors involved in the EOL RSC for EV batteries

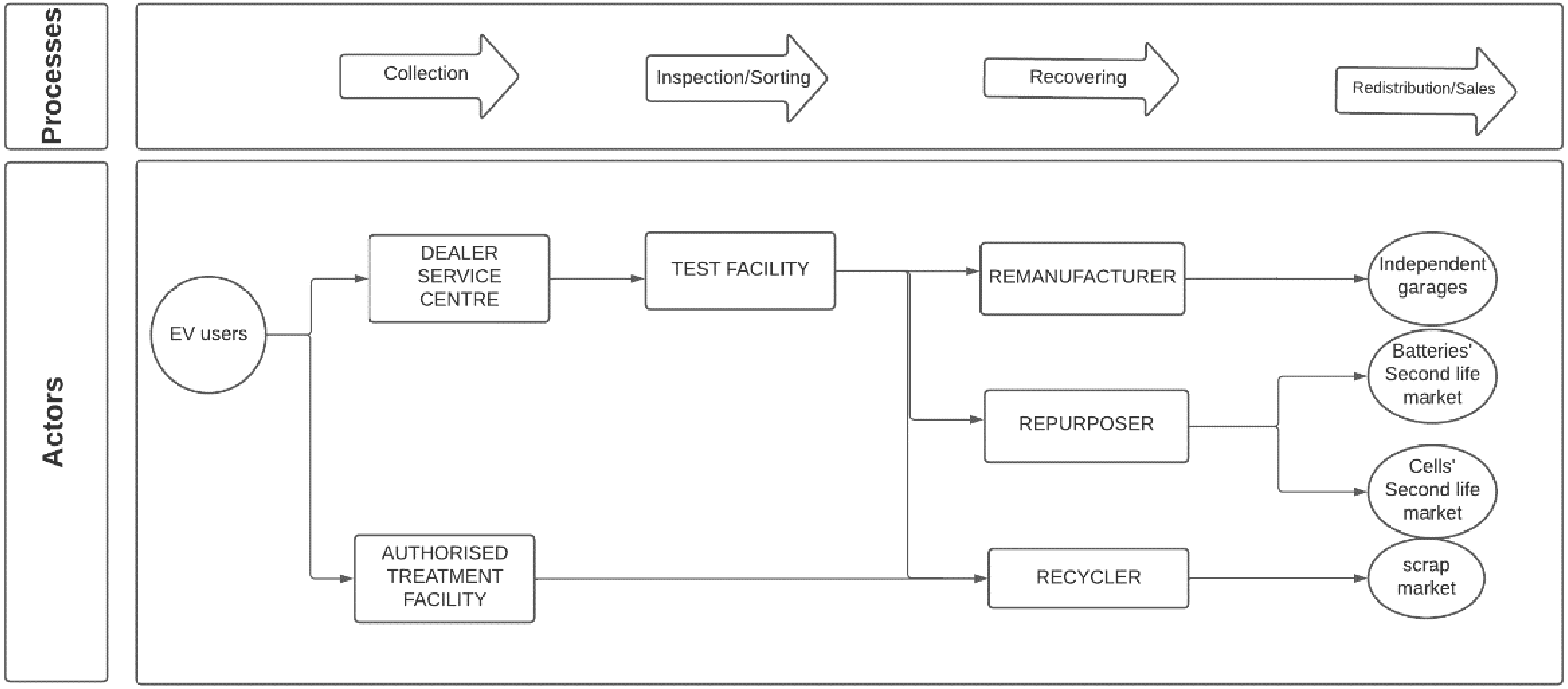


Figure 4.6. Processes and actors in the EOL RSC for EV batteries (Author, 2024)

4.4.3. Relationships in the EOL EV battery industry

EV manufacturers like Audi, Honda, have established partnerships with companies that offer EOL management services for EOL EV batteries. Audi, for instance, has chosen Umicore to establish strategic cooperation. Umicore is a Belgium-based global materials technology and recycling group. Since 2006, Umicore has provided recycling services for lithium-Ion, lithium polymer and Nickel Metal Hydride batteries (NiMH) for diverse applications, including electric cars (Umicore, 2020b). Umicore and Audi have built a partnership to create a closed-loop for EV battery raw materials. As part of the agreement, Umicore will receive cell modules from the Audi e-tron model. The Umicore materials technology experts will be in charge of recovering cobalt and nickel from those cells and processing them into precursor and cathode materials (Umicore, 2020a). According to the results of the first pilot, more than 90 % of the cobalt and nickel in the Audi e-tron can be recycled (Umicore, 2020a). At the beginning of 2020, the companies moved to the next implementation stage, using the recovered cobalt and nickel to produce new battery cells (Umicore, 2020a). In 2020, Honda Motor Europe LTD expanded the partnership agreement with SNAM, which was initially signed in 2013, to extend the sustainable usability of its end-of-life traction batteries and prepare them for 'second-life' renewable energy storage. According to this new agreement, SNAM is responsible for managing EOL batteries from hybrid and electric vehicles in twenty-two countries in Europe (Honda, 2020).

4.5. Sustainable EOL reverse supply chain design and its link with sustainable development

The development of RSC is an environmental strategy that goes beyond pollution prevention strategies that focus mainly on reducing firms' emissions. As it was discussed above, the RSC design aligns with the product stewardship strategy. Product stewardship strategy considers the environmental impact of products throughout the product lifecycle and expands the environmental perspective from a firm to the entire supply chain, including stakeholders and suppliers. Therefore, the reverse supply chain design elements can be aligned with the product stewardship principles to add value through reverse supply operations.

Sustainable development is the last of the three NRBV’s path-dependent organisational strategies. A sustainable development strategy seeks to achieve a firm's growth and development by doing less harm to the environment. This strategy looks for ways to produce in a way that can be maintained over time. Hart (1995) highlights the importance of a shared vision as an essential resource to achieve sustainability by considering the whole product lifecycle from a long-term and proactive perspective. The development of sustainable RSCs aligns with a sustainable development strategy that suggests that to succeed, firms need to account for the environmental impact of their operation and demand a proactive and integrated supply chain which aligns with. According to Govindan, Paam and Abtahi (2016) and Joshi (2022), sustainable supply chains should work to provide advantages towards the three pillars of sustainability: environmental, economic and social. The development of RSC strategies help supply chain to become sustainable over time.

To assess the sustainability of RSC configurations of this research, Elkington (1994) sustainability definition and pillars are going to be used since it is the most well-known and used in the supply chain management literature (De Angelis, Howard and Miemczyk, 2018; Flygansvaer, Dahlstrom and Nygaard, 2018; Batista *et al.*, 2019). As Elkington (1994) suggests, companies seeking to be sustainable should not measure their success only in terms of the financial bottom line but also consider in their assessment the concept of "triple bottom line" (TBL). According to Elkington (1994), sustainability consists of three pillars which are social, economic, and environmental. These pillars constitute the TBL or, as some authors prefer to call, the 3 Ps, People (society), profit (economic) and planet (environment) (See Figure 4.8). The TBL highlights the relevance to assess the effect of firm's decisions on three areas:

Beske, Land and Seuring (2014) categorised sustainable supply chain strategies into the following categories:

- **Strategic orientation:** this category includes the strategic orientation of an organisation. Here, the company's strategic values are presented.
- **Continuity:** is related to the structure of the supply network. This refers to the permanent mode in which the SC partners interact. Therefore, strategies are employed to build enduring partnerships and the evaluation of competent partners.
- **Collaboration:** includes strategic choices concerning the technical and logistical integration of supply chain partners. The objective of joint development is to create new technologies, processes, products, and services collaboratively.
- **Risk management:** is related to businesses implementing a variety of risk management practices in an effort to mitigate threats. The implementation of individual supplier monitoring is a practice that is visible within SSCM.

- **Proactivity:** Organisations can mitigate additional pressure and gain valuable insights through proactive involvement of stakeholders, such as consumers. A proactive approach to the life cycle of a product, beginning with the development phases and continuing throughout its life cycle.

5. Research Design

5.1. Overview

The research design is a plan that helps the researcher to answer his research question. This design should consider the objectives derived from the research question, the sources for data collection, how the data is planned to be collected and analysed, and the ethical considerations (Saunders, Lewis and Thornhill, 2016). This chapter explains the research design used in this study. First, in section 5.2.the justification of the philosophical approach of the study is discussed. Then, the research methods, including the exploratory purpose of the research and the mixed methods approach used in this study, are explained. Afterwards, each of the phases of the sequentially exploratory study (i.e. qualitative phase and quantitative phase) are presented along with the data collection process, techniques used to ensure validity and reliability and how the data is planned to be analysed. Finally, the ethical considerations of this study are explained.

5.2. Research philosophy

After analysing some of the most common philosophical paradigms used in business and operation management research, the author's industry background, and the research problem, it has been identified that Pragmatism is the most suitable paradigm to guide this research aims to contribute to the development of reverse supply chain and sustainable supply chain theory which is still in a developing stage. Pragmatism is a well-known philosophical approach widely used in business research (Lee and Lings, 2008). The pragmatism paradigm sees the world as a group of actions, situations and consequences, not as antecedent conditions like the post-positivism paradigm (Creswell, 2014). Pragmatism seeks to understand the world using available theories to simplify reality and find a solution to a problem (Patton, 1990) by suggesting practical solutions to advise future research and practice (Saunders, Lewis and Thornhill, 2016) . Moreover, as Rossman and Wilson (1985) suggest, instead of focusing on research methods, pragmatism focuses on the research problem and is not limited to using a specific method; instead, it uses all the research approaches available to understand a problem better.

One of pragmatism's main characteristics is that it suggests that meaning and truth should only be defined based on how useful they are in action (Lee and Lings, 2008). Pragmatism has been successfully used in sustainable supply chain research (Batista *et al.*, 2021; Aarikka-Stenroos *et al.*, 2022). In these pieces of research Batista *et al.* (2021) and Aarikka-Stenroos *et al.* (2022), the authors chose the pragmatic philosophical approach to find solutions to recent sustainability issues in the supply chain field, extend the theory development of this growing body of literature and provide empirical contributions. Through their research, Batista et al. (2021) and Aarikka-Stenroos et al. (2022) provide guidance for industry practitioners and develop useful tools that can be applied in an industry context.

In this research, problems related to the design of RSC aree identified, and this research aims to find solutions to these problems by exploring sustainable design opportunities. The pragmatism paradigm has influenced mixed-methods research designs. Both qualitative and quantitative methods are commonly used in pragmatism-guided research (Saunders, Lewis and Thornhill, 2016). The decision about what method or combination of methods should be used depends on the nature of the research. For this study, like in previous research guided by the pragmatism paradigm, a mixed-methods approach that combines qualitative and quantitative methods is used. This research follows a sequential process with two main phases. In the first phase, qualitative data is collected from interviews with managers and directors from companies involved in the EoL management of EV batteries. While in the second phase, quantitative and qualitative data are collected through interviews and questionnaires sent to a group of supply chain managers and directors engaged in the EV battery industry. The mixed methods approach is chosen for this study to understand the complexities of the EoL reverse supply chain, foment discussion and assess different sustainable UK EoL RSC EV battery designs.

One of the main characteristics of the pragmatism paradigm is that our minds decide what may be considered knowledge and that all our beliefs are revisable according to our experience (Hollis, 1994). For pragmatism, there is no final unique theory of truth; instead, it interiorise facts to a so-called “web of beliefs”, and it can replace a theory of truth with an equivalent between what is true and what is more simple or useful to believe (Friedman and Friedman, 1953). In the past, academics and practitioners used to pay attention to the forward flow of supply chains and did not have any incentive to analyse the reverse flow. In such context, specific theories and rules were created and applied. However, in the last decade the context has changed, societies have changed, and the demand for sustainable operations has changed the way companies operate. Therefore, businesses have been forced to adapt, and so have the theories that ruled the supply chain configurations (Gobbi, 2011; Gupta, 2012). Hence, it may be inferred that the way to create knowledge within the sustainable reverse supply chain environment needs to be adapted too. This research uses the NRBV theory, which, although it has not been largely applied in the SCM field like other well-established theories, has proved helpful in recent sustainable supply chain research (see for examples: Masoumik *et al.*, 2014; Miemczyk, Howard and Johnsen, 2016; Ashby, 2018).

5.3. Research methods

A wide range of methods and approaches are used in Operation Management (OM) research (Karlsson, 2009). According to Sodhi and Tang (2014) some of the most used approaches in OM are **analytical, behavioural, case study and empirical**. Each of these approaches serve different roles in the creation of knowledge. **Analytical modelling** is widely used approach in operation management. In analytical modelling the results are deducted from theoretical principles from computer science, engineering or mathematics. Some examples of analytical modelling are mathematical optimization methods are, and simulation used for solving real and complex operations problems (Sodhi and Tang, 2014). Good analytical model can help to understand how one variable may cause a certain effect. Some examples of the application of analytical modelling in RSC may be found in (Ghorbani, Arabzad and Tavakkoli-Moghaddam, 2014; Jindal and Sangwan, 2014; Das and Dutta, 2015). **Behavioural approach** on the other hand can be applied by conducting experiments to infer the decision-making process. Several authors have used behavioural experiments to study different OM issues such as information sharing, coordination, supplier relationships in the context of supply chain management (Croson, Donohue and Donohue, 2006; Croson *et al.*, 2014). **Empirical research** can be used to document the state of the art in operations management, as well as to provide a baseline for longitudinal studies. It can also be invaluable in the development of parameters and distributions for mathematical and simulation modelling studies (Flynn *et al.*, 1990). Empirical research usually starts with a hypothesis formulated based in the literature. Then, data is collected to validate the construct and test hypothesis. Afterwards, the results are analysed and discussed to identify or test the relationship between constructs (Sodhi and Tang, 2014). Finally, according to Sodhi and Tang (2014) **case study** has been one of the most influential methods in OM research due to its appropriateness to study complex management issues, especially in the development of new theory. Case research provides an excellent and useful approach to studying emergent practices and complex management issues (Karlsson, 2009). Moreover, case studies have been successfully applied in the RSC and CLSC research (Jayant, Gupta and Garg, 2014; Ashby, 2018; Jabbarzadeh, Fahimnia and Sabouhi, 2018; Batista *et al.*, 2019; Pal, Sandberg and Paras, 2019; Russo, Pellathy and Omar, 2020).

Research can have an **exploratory,** descriptive, explanatory, or evaluative purpose (Saunders, Lewis and Thornhill, 2016). Due to the newness of the sustainable supply chain field, there is a need for more exploratory research to accumulate and learn from new empirical evidence. Exploratory research is particularly common in sustainable supply chain case studies as seen in Schenkel *et al.* (2015); Bernon, Tjahjono and Ripanti (2018). The purpose of this research is exploratory. An exploratory study helps ask open questions to discover what is happening and clarify the understanding of the problem being studied. Usually, the research questions that have an exploratory purpose begin with “what” and “how” and the questions that are asked during the data collection to explore a problem most likely start with “what” and “how” too. The limited literature on RSC design for developing industries demands more use of exploratory approaches. The research questions of this research are:

- ***RQ1:*** *What are the requirements for designing a sustainable EoL RSC in an emerging sector?*
- ***RQ2:*** *How can an EoL RSC be designed to meet operational and sustainability objectives?*

The “what” and“how” questions in these research questions are aligned with the exploratory approach used to discover new insights to develop sustainable reverse supply chains.

The next decision is related to the methodological choice, which can be qualitative, quantitative or mixed-methods (Saunders, Lewis and Thornhill, 2016). Quantitative research is used to study the relationship between variables. These variables are measured numerically and analysed using statistical and graphical techniques. Quantitative research usually uses control measures to assure data validity. This method also uses probability sampling to ensure generalisability. Qualitative research, on the other hand, is used to study the participants' ideas and the relationships between them. This type of research uses several data collection techniques and analytical procedures to develop conceptual frameworks and theoretical contributions. In qualitative research, the meanings are obtained from words and images. The qualitative data collected is non-standardised, so it usually must be classified to conduct the correspondent analysis. Both quantitative and qualitative research designs may use a single data collection technique (e.g. questionnaire or interview), called the mono method or multiple data collection techniques, called multi-method (Saunders, Lewis and Thornhill, 2016).

Mixed-methods research integrates qualitative and quantitative data collection techniques and analysis procedures. Depending on the qualitative and quantitative methods sequence, the research design can be concurrent, sequential exploratory, sequential explanatory, or sequential multi-phase (See Figure 5.1) (Saunders, Lewis and Thornhill, 2016).

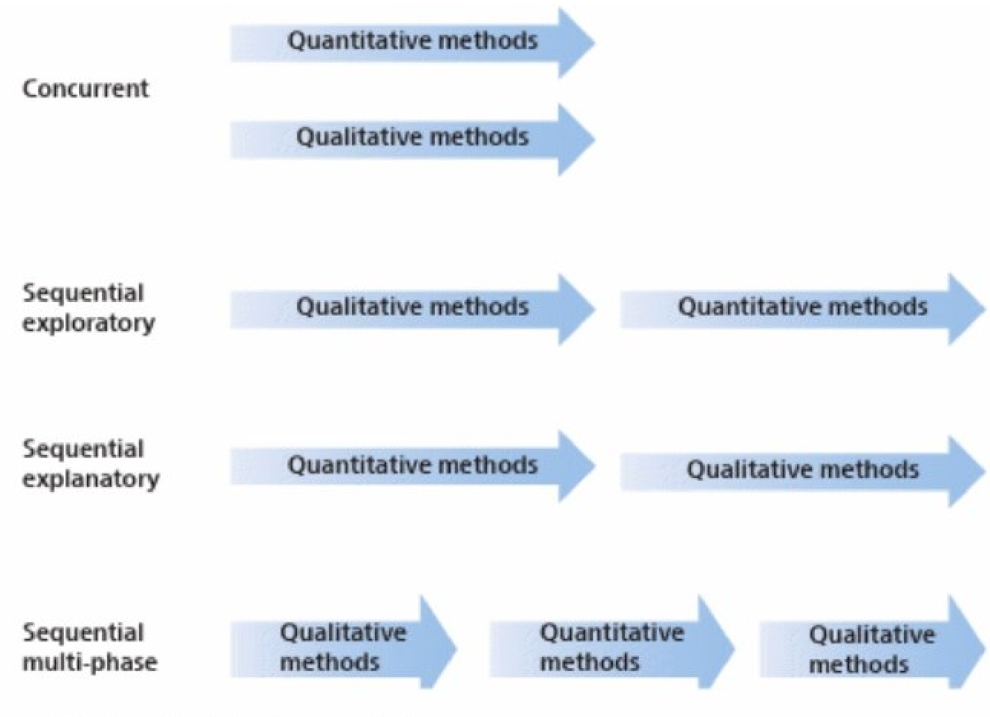


Figure 5.1. Mixed methods research design (Sourced Saunders, Lewis and Thornhill, 2016)

For this research, a mixed-methods sequential exploratory case study approach that combines qualitative and quantitative methods was chosen since it was considered more appropriate to understand better the research problem chosen. The decision to adopt a mixed-methods exploratory case study approach aligns with the pragmatism paradigm, that uses the available theories to simplify reality and find a solution to a problem by suggesting practical solutions to advice future research and practice (Saunders, Lewis and Thornhill, 2016) .

The sequential exploratory method for this case study research begins with a qualitative phase that includes an extensive review of the literature to understand the EV battery RSC context and RSC design objectives. Then qualitative data is collected from the industry through semi-structured interviews to validate the findings and gain new RSC design insights from an industry perspective and the expected future RSC challenges **(More details in Section 5.4. Qualitative Phase).** A practical evaluation framework is created with insights from the literature review and interviews. Then, the insights collected in the first stage are used as input for the next phase, which is the quantitative phase. The final phase of the mixed-methods process includes collecting quantitative data from primary sources to use as insights to build up a simulation model and assess alternatives to improve the sustainability of RSC configurations **(More details in Section 5.5. Quantitative Phase)**. The quantitative data is analysed to interpret the results and draw conclusions. The research design chosen allows the researcher to have a holistic understanding of how companies in the selected industry can design sustainable EoL RSC to address the future challenges of the EV battery industry. A summary of the methodological framework for this research may be seen in Figure 5.2.

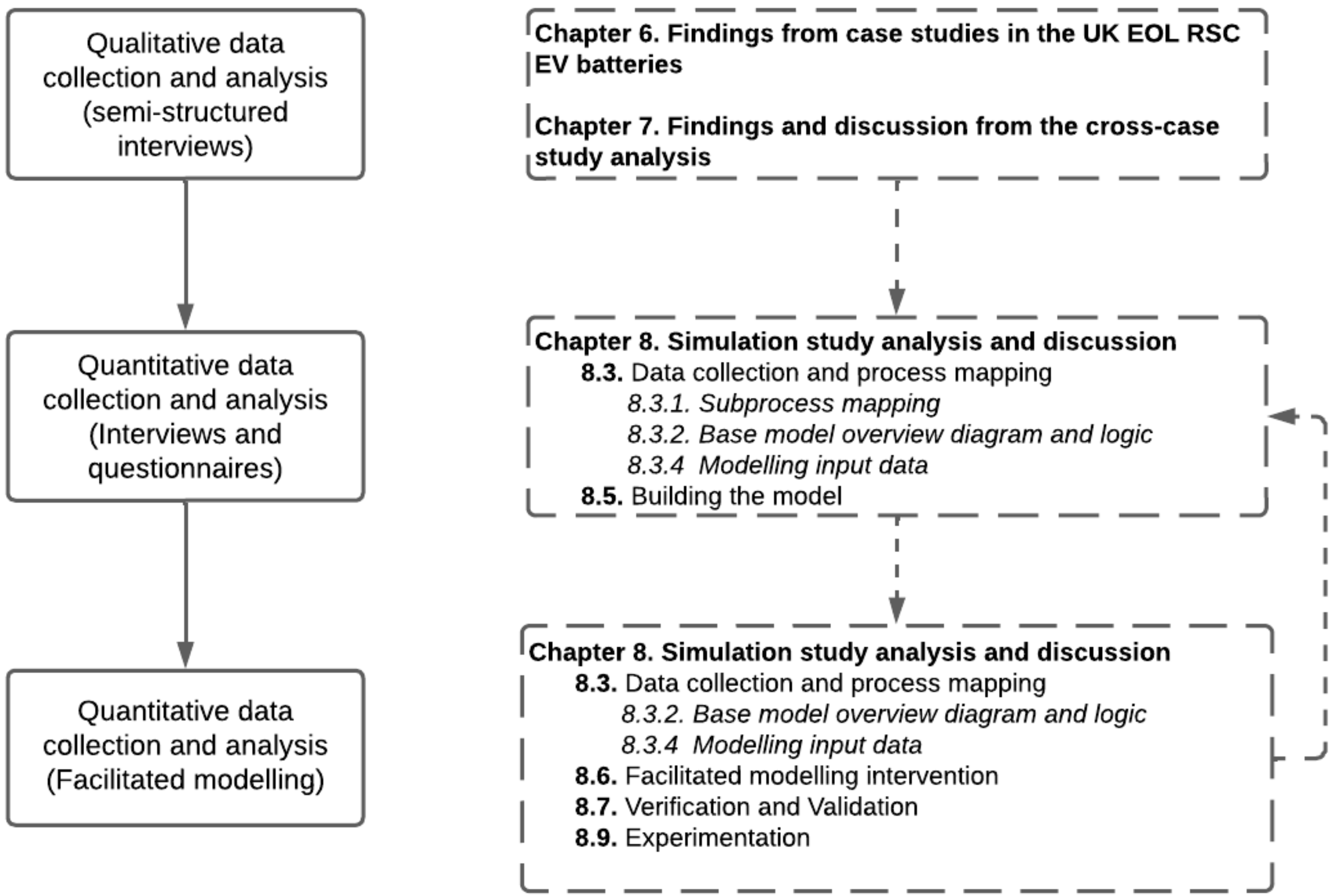


Figure 5.2. Methodological framework (Author, 2024)

5.4. Qualitative phase (First Phase)

5.4.1. Case study

Given the exploratory nature of this research, an intercompany case study is selected. As Yin (2009) suggests, case studies provide new and valuable insights for knowledge development since they allow an in-depth study of a specific case in its original context to provide richer insights (Yin, 2009; Denzin and Lincoln, 2011). During the last years, case study research has become popular in the SCM field since, as Halldorsson and Aastrup (2003); Da Mota Pedrosa, Näslund and Jasmand (2016) suggest, case studies have greater applicability than other traditional methods. Case study-based research has been widely used during the last years in the operation management and supply chain management field and has proved to be helpful in understanding RSC and CLSC complexities as seen in the publications by Jayant, Gupta and Garg (2014); Ashby (2018); Jabbarzadeh, Fahimnia and Sabouhi(2018); Batista *et al.* (2019); Pal, Sandberg and Paras (2019); Russo, Pellathy and Omar (2020).

Moreover, in the practical context, according to Karlsson (2016), case studies have a high validity among practitioners and allow replicability as long as the research has strict methodological rigour and follows a systematic procedure. As Stuart *et al.* (2002) suggest, to have methodological rigour, case studies must follow a strict process that includes the following steps: research question definition, instrument development and site selection, data gathering, data analysis, and research findings dissemination.

The selection of a case study strategy is also in line with the three conditions proposed by Ying (2009). Firstly, the research questions include "what" and "how'" because this research aims to understand what are the requirements to develop a sustainable EoL supply chain and how to design a RSC in a particular industry context. The second condition related to the control of behavioural events is also met. The third condition requires that the research focus on contemporary events that are also complied with by this research since the literature of RSC is relatively new in the field and is under constant development. This research presents an intercompany case study in the context of the UK end-of-life supply chain for electric vehicle batteries.

Figure 5.3 shows some of the main actors of the UK EoL RSC for EV batteries. As it may be seen in the legend, the blocks represent the companies that participate in the EoL management of EV batteries. The arrows represent the material flows (e.g. batteries and components) and the circles the markets for the recovered components and materials.

The companies **highlighted in bold** represent the universe of data collection sources of this study.

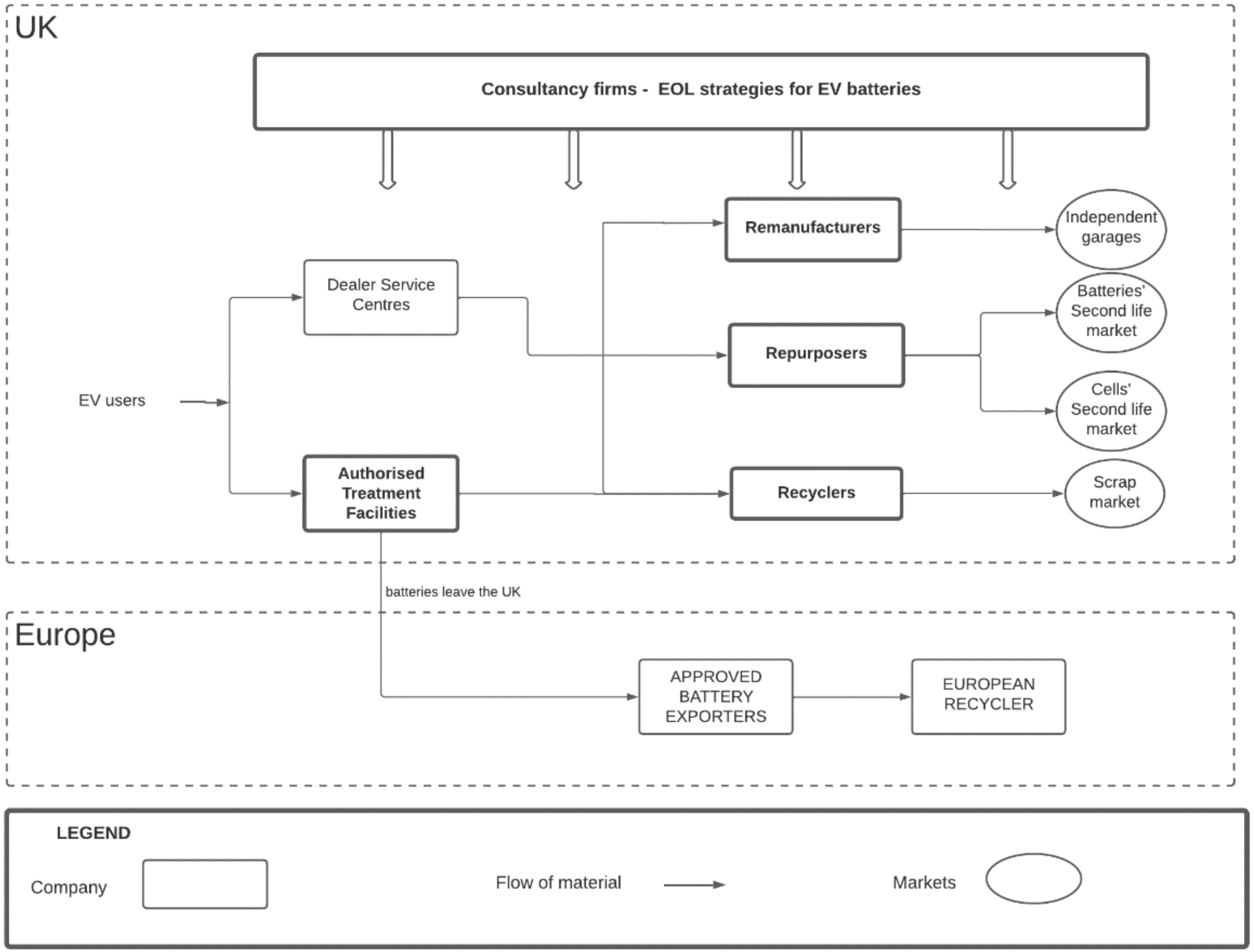


Figure 5.3. UK EoL RSC EV battery actors (Author, 2024)

5.4.2. Data collection

As Yin (2009) suggests, interviews are one of the main sources of case studies. In an interview, the interviewer asks either precise or general questions about a topic and listens to the interviewee talking. In the research context, an interview is a guided conversation between two or more people (Saunders, Lewis and Thornhill, 2016). Interviews can help get explanations of events and processes from the participants as well as the participants' relative perspectives. In this research, the units of analysis of the case study are the companies that belong to the UK EoL RSC for EV batteries. The data collection sources are interviews with managers and directors from companies involved in the EoL management of electric vehicle batteries.

Interviews can be categorised into structured, semi-structured and unstructured (Saunders, Lewis and Thornhill, 2016). Structured interviews are conducted using a standardised questionnaire developed by the researcher. In structured interviews, the researcher asks all the participants questions from the questionnaire, which are read literally and in the same tone to avoid bias. In contrast, semi-structured interviews are not standardised. In semi-structured interviews, the researcher prepares a list of themes and potential key questions related to the themes to use as a guide. The last type of interview is unstructured, informally called in-depth interviews. This type of interview is used to explore a general topic of interest. In-depth interviews do not use fixed themes and questions. The questions are formulated throughout the interview to explore and identify emerging topics. It is crucial that the questions and prompts only come from what the interviewee shares.

The types of research interviews can also be differentiated by the number of participants and the way they are conducted e.g. face-to-face interview, telephone interviews, internet-mediated interviews, and focus groups (See Figure 5.4) (Creswell and Creswell, 2018).

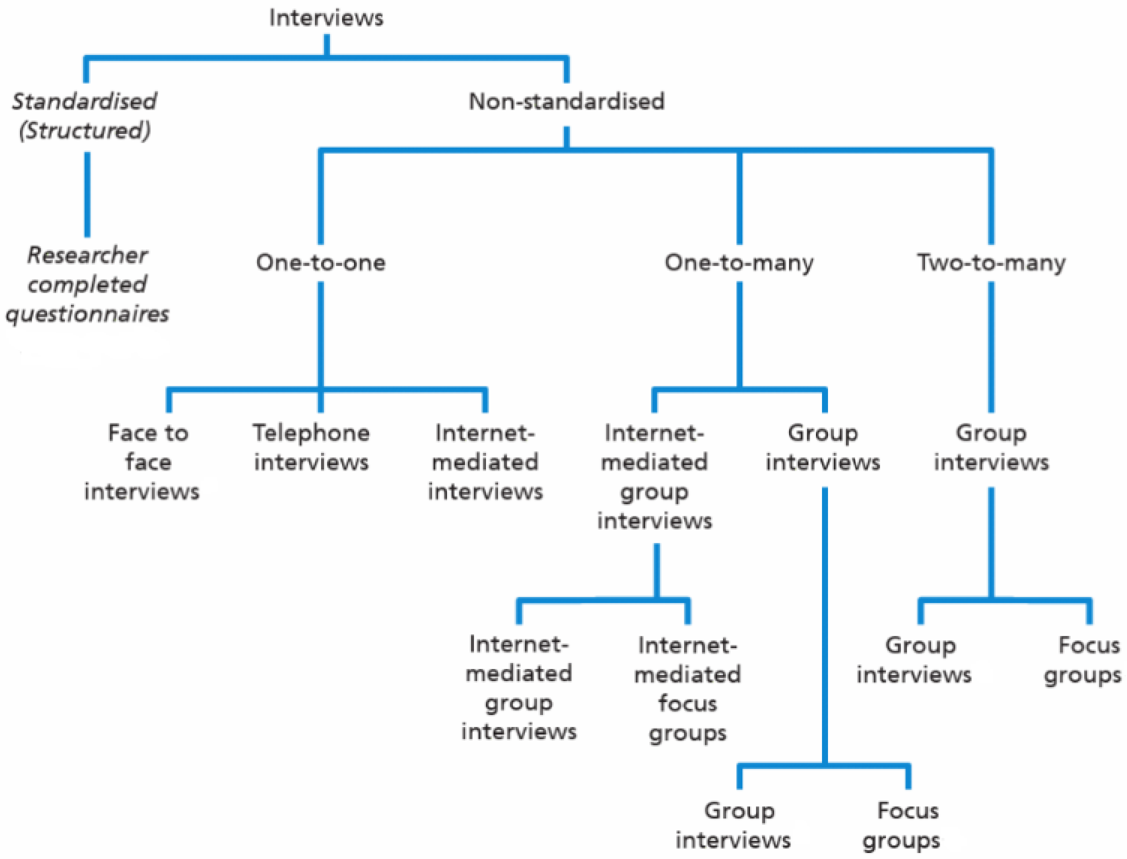


Figure 5.4. Interview modes (Saunders, Lewis and Thornhill, 2016)

The RSC of EV batteries that is being studied is still in a developing stage. Hence, this research has an exploratory nature. For the first phase of this research, the researcher did a secondment with **ConsultancyFirm_A.** During the secondment, the researcher had the opportunity to learn about the UK EV battery industry and the main stakeholders from Circular Economy Manager, Battery Technology solution Lead and Research & Innovation manager. Some of the main activities undertaken were mapping the EoL processes, identification of the inefficiencies of the process, and building up a general simulation for the main EoL processes.

Semi-structured interviews were identified as the best data collection method to collect the specific data for this study. In contrast to other methods, such as questionnaires, semi-structured interviews are more flexible. Semi-structured interviews allow the researcher to guide the interview around specific themes: Drivers and barriers to implementing environmental strategies, EoL Reverse supply chain design and Sustainable Reverse supply chain. However, at the same time the flexibility of this type of interview allows the participants to explain their ideas in their own words and to request clarifications when necessary. The flexibility of semi-structured interviews is necessary for this type of research that needs to explore a topic and industry that is still developing.

This research presents a multiple case study in the context of the UK end-of-life RSC supply chain for electric vehicle batteries. The unit of analysis is the EoL RSC for EV batteries that consists of all the parties and processes involved in collecting EV batteries from the customers to recover value. An important decision to make at the beginning of a case study research is to select the specific cases to study to answer the research questions and achieve the research objectives. According to Saunders, Lewis and Thornhill (2016) and Miles and Huberman (1994), purposive sampling is commonly used in case study research when the researcher aims to understand a particular topic as much as possible . **Purposive sampling** is adopted in this research to gain an in-depth understanding of the current situation of the companies involved in the developing UK EoL EV battery supply chain. The first criterion was that the RSC parties have experience providing EoL services to the automotive industry and have worked or have run pilots with EV batteries. The second criterion was that the RSC parties should also be responsible for different stages of the EoL management of EV batteries to capture as much information as possible about the reverse supply chain. Patton (1990) suggests that the sample size depends on what the researcher aims to learn, its usefulness and the available time and resources. The participants of this case study were selected using purposive sampling. Two of the most important authors in the case study research, such as Eisenhardt (1989) and Yin (2009), suggest different ideal sample sizes for case studies. Eisenhardt (1989) and Yin (2009) suggest that the ideal number is between 4 and 8 cases. There are several examples of in-depth multiple case studies in the CLSC and Sustainable supply chain area that have used between 2 to 4 as number of cases (Das and Dutta, 2015; Schenkel *et al.*, 2015; Miemczyk, Howard and Johnsen, 2016; Pal, Sandberg and Paras, 2019). For this case study, the number of case studies selected was five which is appropriate according to the case study literature and recent research in the field. To find the cases for this study, the researcher contacted the managers and directors of a group of companies that collaborated in an ongoing UK EoL EV battery research project and a car manufacturer with operations in the UK. Within the EV battery remanufacturers, Remanufacturer_A was chosen for this study. Remanufacturer_A is a small company that has done some refurbishing work in the past and has experience working in some refurbishing and remanufacturing pilot projects with electric vehicle batteries. Scrap car recyclers are the companies that buy cars from car users as scrap to recycle their materials, and to do so, they work with a network of independent Authorised Treatment Facilities (ATFs). ScrapCarRecycling_A was chosen for this research since it has one of the largest Authorised treatment facility networks in the UK that receives EVs and extracts their corresponding EV batteries. Recycler_A is a UK-based material recycling company that offers lithium-ion battery recycling services with a dedicated factory area and specialised personnel. Another important actor of the UK RSC for EV batteries that help to extend the life of the EV battery components are repurposing companies. Repurposer_A was chosen for this study since it is developing projects to build Lithium-ion batteries for storage applications using used EV battery cells. All these companies are based and operate in the UK. Finally, OEM_A was selected because it is an established automotive manufacturer with presence around the world including the UK with a range of electric and hybrid cars.

According to Forza (2002) companies are a common unit of analysis in industry research and the only way to obtain information regarding these companies is through the people that work at them. Due to the hierarchical levels within organisation, and the different roles and specialisation of workers certain people can be more knowledgeable about certain topics than others (Forza, 2002). Therefore, to achieve the research objectives the key informants of the case studies were carefully selected. In organisational research a key informant is chosen because of its hierarchical position in an organisation, first-hand experience working in its department, expertise and wide knowledge of the subject studied and his capability and willingness to share information requested (Kumar, Stern and Anderson, 1993). Krause, Luzzini and Lawson (Krause, Luzzini and Lawson, 2018) and Woodside and Wilson (2003) suggested if only one key informant in the organisation has capacity to provide an unbiased view of the unit of analysis it is possible to rely on a single informant.

For this research the following key informants for each case study were selected for the following reason:

- Director_Reman_A was selected as key informant of Remanufacturer_A because of his 17 years as Managing director of Remanufacturer_A. Remanufacturer_A is a small company and Director_Reman_A has led and supervised previous successful remanufacturing programs for automotive companies. The director of Remanufacturer_a is the main responsible and leader of the EV remanufacturing projects that the company has been developing.
- Manager_SCR was chosen as ScrapCarRecycler_A's key informant. Manager_SCR has 9 years of experience working as Managing Director of ScrapCarRecycler_A and has wide knowledge of the EoL vehicle industry. He is in charge of leading the electric/hybrid EoL battery handling services and operational training of Authorised Treatment Facilities' staff.
- Manager_Recycler_A was selected as the most appropriate key informant of Recycler_A. Manager_Recycler_A has more than 4 years working as Business Manager of the Battery Recycling division of the company. He has been the responsible for the development of the lithium-ion battery business since the beginning.
- Director_Repurp_A, Head_Grants_Repurp_A, PM_Repurp_A were chosen as key informants of Repurposer_A that start operating in 2016. Director_Repurp_A has been Repurposer_A Director of Operation for nearly two years. Director_Repurp_A is the responsible of planning and managing the operational part of the company projects. Director_Repurp_A is currently leading projects to demonstrate the viability of the use of waste cells to build new batteries for energy storage applications. Since Director_Repurp_A has been working in the company for a relatively short time Head_Grants_Repurp_A, PM_Repurp_A were selected as well as key informants due to their experience on developing the project to produce Repurposer_A batteries with waste cells.
- Manager_OEM_A was selected as key informant since he has more than 15 years of experience working at OEM_A. In his current managerial role he is

responsible for the company's environmental planning in the European region.

Table 5.1 shows the companies the coding names of the companies that participated in the case study, the key informants and the duration of the data collection.

Table 5.1. Profile companies and interviewees

Coding name company	Type of company	Coding name interviewee	Interviewee/ Key informant	Time spent
Consultancy_firm_A	Consultancy firm specialised in EV battery circular economy projects	CEManager_CF BTLead_CF, R&IManager_CF	Circular Economy Manager, Battery Technology Solution Lead, R&I manager	3 months secondment
Remanufacturer_A	Remanufacturer/ Refurbisher	Director_Reman_A	Managing Director	2 hour
Recycler_A	Battery Recycler	Manager_Recycler_A	Business Manager	1.5 hours
ScrapCarRecycler_A	Scrap Car Recycler that lead ATF network	Manager_SCR	Senior Manager	1.5 hours
Repurposer_A	Repurposing company	Director_Repurp_A, Head_Grants_Repurp_A, PM_Repurp_A	Operation Director, Project Manager	4 hours
OEM_A	Car manufacturer	Manager_OEM_A	Environmental Planning manager	3 hours

A semi-structured interview protocol was shared with each participant before the interviews. All the interviews were designed to last between 1 – 1.5 hours to allow enough time to collect the necessary information while not exhausting the interviewee. The semi-structured interview themes were aligned with the research questions, study objectives and the constructs of the conceptual framework: Drivers and barriers to implementing environmental strategies, EoL Reverse supply chain design and Sustainable Reverse supply chain. Even though the general themes of the interviews were fixed and aligned with the conceptual framework, the questions were flexible to allow further exploration.

To ensure the validity of the interview data collection, the interview protocol was shared with the Battery Technology Solution Lead and Circular Economy Manager of

ConsultancyFirm_A. ConsultancyFirm_A has worked on several EoL EV battery projects with Remanufacturer_A, Recycler_A and ScrapCarRecycling_A. Sharing the interview with ConsultancyFirm_A was useful to assess the questions' appropriateness, coherence and clarity. ConsultancyFirm_A has years of experience working directly in EV battery-related projects with some of the selected companies and the managers and directors interviewed; know about the sector and EV battery projects in which these companies are involved. Based on the feedback given by ConsultancyFirm_A, the questionnaire was adapted.

The data collection took place from January 2021 to August 2022. In total, 9 semi-structured interviews were conducted with 5 companies. From 9 semi-structured interviews, 3 of these interviews were one-to-one and the other six one-to-many. The interviews were conducted through MS Teams videocall. The reason why the internet-mediated interview was selected was due to the Coronavirus pandemic and the change in working habits. On March 2020, a lockdown was imposed in the UK, which was posteriorly lifted in May. After all the restrictions were lifted in the UK, some companies have continued adopting remote working. All the interviewees at the time of the secondment and further interviews were conducted while the participants were working from home, hence the MS Teams video calls were chosen as the most appropriate interview mode. Besides the information collected in the interviews, multiple sources of secondary data were used, such as company reports, project reports, companies' websites, government databases and news articles for information triangulation and validating the insights from the interviewees.

5.4.3. Validity and reliability

Aligned with the framework developed by Voss, Tsikriktsis, Frohlich (2002); Barratt, Choi, Li (2011) and Yin (2009) four criteria were used to evaluate the case study research. These criteria were internal validity, construct validity, external validity and reliability. Table 5.2. summarises the measures taken to address the four criteria (internal validity, construct validity, external validity and reliability) , ensure methodological rigour and quality of the research approach.

Table 5.2. Case study validity and reliability criteria and actions taken (Author,2024)

Case study criteria	Actions taken	Phase of research
Internal validity	- Representing the data and outcomes in tables and comparison tables to identify patterns and facilitate the analysis	Data Analysis
Construct validity	- Validating the coherence of interview outcomes with company reports, project reports, companies' websites, and internal news articles. - Presenting preliminary findings to interviewees to get feedback and validate the interpretations.	Data collection
External validity	- Use of existing theories for the development of the conceptual framework (e.g. NRBV, circular economy) - Collecting information from multiple companies involved in the RSC for EV battery to minimise researcher bias.	Research design Data collection
Reliability	-Developing and structured research design - Developing and using an interview protocol - Developing a database with interview recordings, transcripts, summaries	Research design Data collection

5.4.4. Data analysis

The first step of the data analysis was the documentation which started with the data collection process. After each interview, the data collected was documented by transcribing video calls and gathering other supportive documents shared by the interviewees. Besides the transcripts, key ideas and impressions were written immediately after the interviews to avoid forgetting and missing important information (Voss, Tsikriktsis and Frohlich, 2002).

Once the transcripts were ready, the data was cleaned by eliminating any transcription errors to ensure transcription accuracy. After finishing the transcript and the notes, a transcript summary was prepared. As Saunders, Lewis and Thornhill (2016) suggest, a summary transcript is used to compress a long statement into brief ones that make sense of what has been said and rewrite it in fewer words. To analyse the data, the thematic analysis approach was used. The thematic analysis was used to seek themes or patterns throughout the data set. Conducting a thematic analysis involves four main steps: becoming familiar with your data; coding your data; searching for themes and recognising relationships; refining themes and testing propositions (Saunders, Lewis and Thornhill, 2016).

The familiarisation with the data started during the writing up of the transcript and by generating the summary. The familiarisation process was iterative and continued throughout the research project. After the initial familiarisation with the data, this data was coded to structure and organise the extensive data set collected and categorise data with similar meanings. The coding procedure consists of assigning labels to the units of data found within the data item, which in this case is the interview transcript.

When selecting the codes to be used, researchers can use three sources: labels from data collected by the researcher, terms used by participants - "in vivo" or existing theory and literature – "a priori" See Figure 5.5. After coding the data set, the main themes were identified. A theme is a general category that incorporates several codes that seem to be related between each other and suggest an idea that is relevant to the research question (Saunders, Lewis and Thornhill, 2016). For this research, as it is supported by previous literature and theories, "a priori" codes and themes were chosen and extracted from previous sustainable and CLSC research. Once data is reduced through the coding and themes identification, the case studies can be further analysed.

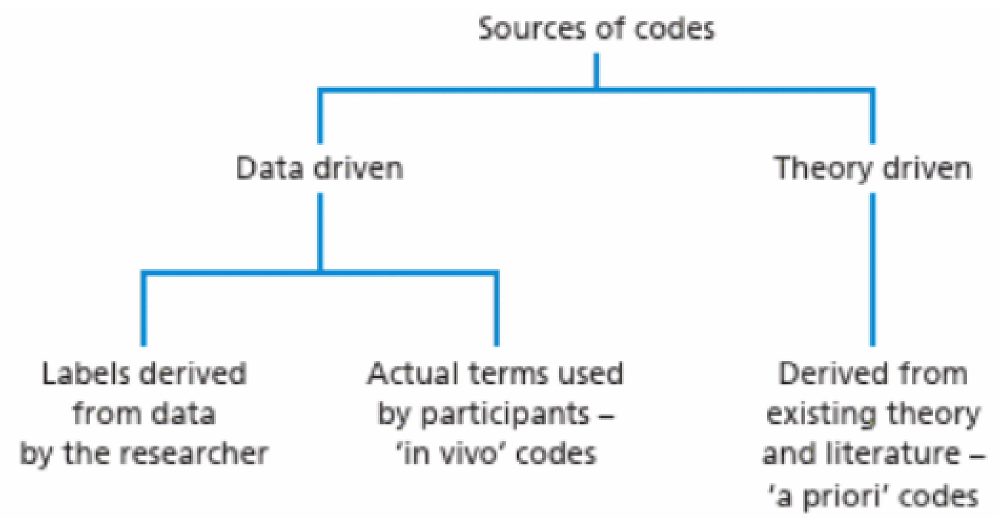


Figure 5.5. Sources of code (Saunders, Lewis and Thornhill, 2016)

According to Eisenhardt (1989b), case studies should be analysed following two steps. The first step is within case data analysis and then the search for cross-case patterns.

In the within-case analysis, each company case was analysed individually. For each company case, the researcher tried to identify the main drivers and barriers of the EOL industry, EOL Reverse supply chain design and RSC sustainability strategies. The data was organised in arrays in MS Excel to organise the supporting evidence per case. For the cross-case analysis, all the cases and tables were organised, forming a large array to look for the cross-case patterns. To ensure the correct identification of cross-case patterns, three steps were followed: selection of a category to identify group similarities and differences, chose pairs of cases to look for similarities and differences, and divide the data by data sources (Eisenhardt, 1989b; Voss, Tsikriktsis and Frohlich, 2002). The cross-case analysis allowed the comparison of each company case against the conceptual framework constructs and the discovery of novel findings. The initial conceptual framework and its three main constructs elements were updated with the findings of the cross-case study analysis.

5.5. Quantitative phase (Second Phase)

As it was mentioned above, this research follows an exploratory sequential. In the first phase, qualitative data was collected and analysed. The insights of the first stage were used as input for the next phase, which is the quantitative phase. For the quantitative phase, a simulation study was conducted. The use of simulation for this research will allow the design of a highly flexible model to represent a variety of system configurations to assess sustainability strategies.

5.5.1. Case study

In the second part of the case study a model of the UK end-of-life supply chain design and metrics to assess the economic and environmental sustainability of the operations is elaborated. To model the RSC of this study, a simulation approach was chosen. Simulation has been widely used as a problem-solving tool to address different RL and CLSC problems, such as network design, facility location, capacity planning and system configuration (Hai-jun *et al.*, 2007; Vlachos, Georgiadis and Iakovou, 2007; Georgiadis and Besiou, 2008; Yanikara and Kuhl, 2015; Chen *et al.*, 2018).

Modelling a future sustainable EoL reverse supply chain poses different challenges. In the case of the EV battery industry, its UK EoL reverse supply chain is still in a developing stage. Also, the EOL routes for EV batteries are not clearly defined yet. The technology for recycling, recovery and remanufacturing is still under development. The service providers and companies that offer EoL services are handling low volumes of batteries, and the markets for recovered products and materials are still being explored. Moreover, the legislations around the EoL treatment of EV batteries are subject to change. Currently, the legislations focus mainly on the recycling alternative, not the other options such as remanufacturing and repurposing. For these reasons, it is uncertain what is going to happen in the future with UK EoL RSC for EV batteries. Due to the characteristics of research context chosen that focuses in the future UK EoL RSC for EV batteries that does not exist yet, is highly unpredictable, has limited historical data a facilitative modelling approach was chosen.

Facilitated modelling is the process used by the facilitator to create models jointly with a group of people from a client organization with or without the assistance of a technological tool (Eden and Radford, 1990). Facilitated models are used to understand better the studied problem, articulate preferences to value the outcomes of the analysis and facilitate the implementation of the different recommendations. As Robinson *et al.* (2014) suggest the purpose of a facilitative simulation modelling is to develop understanding of an specific topic, promote discussion by using simulation model as a supporting tool.

The industrial scope of this model includes the most relevant companies in the UK RSC EV batteries supply chain, such as ATFs, dealer service centre, remanufacturing company, repurposing company and recycling company. This research draws on the information from managers and directors from companies that have experience providing EoL services to the automotive industry and have worked or run pilots with EV batteries. Regarding the supporting technology, as the interviews with the companies were conducted online, Miro platform was used to share live with the participants the main notes of the discussion and the draft of the process map. Once the process map is defined and the main estimations of the process figures are collected, these were used to build up a simulation model in Arena 14.1v to do the experiments.

The simulation study objectives, data collection, model description, verification and validation, and data analysis techniques used are described in detail in **Chapter 8. Simulation study analysis and discussion.**

5.5.2. Simulation study objectives

The objectives of this simulation study are the following:

- To build a facilitative simulation model that supports the design of an emerging EoL RSC for EV batteries.
- To run a set of simulated scenarios to explore how different sustainability strategies affect the RSC design configuration, capacity, economic impact (i.e. value of material recovered, production savings), environmental impact (i.e. batteries recovered, batteries remanufactured, batteries for a second life, kg of materials recovered, CO_2 emissions reduction)

5.5.3. Data collection and process mapping

Purposive sampling is a non-random selection of participants for a study. The participants must be well-informed about the study's objectives and willing to share that information with the researcher. To collect the data for the simulation study, purposive sampling was chosen. Purposive sampling was used to select the companies involved in the EoL management of EV batteries with more information about the processes studied (e.g. batteries collections, recycling, remanufacturing, repurposing) and openness to share quantitative data. Probability sampling could not be used due to time and resource constraints caused by the global pandemic.

Data collection is an important part of a simulation study. The data requirements to build a simulation model can be divided into two groups (Greasley, 2004):

- Data for the process map: It includes process routing and decision points. With this information, a diagrammatic representation of the process to be analysed can be built.
- Additional data for the simulation model: It includes process timing, resource availability, demand pattern, and process layout.

Information about the subprocesses performed by each company involved in this study was collected to build the case study of the end-of-life supply chain network for electric vehicle batteries. A new proposed process map and model was developed with the initial information of the subprocesses and the interview findings about the future expectations for the UK EoL RSC for EV batteries.

There are different data sources that can be used for data collection in simulation studies (See Table 5.3)

Table 5.3. Data sources in simulation study (Sourced: Greasley, 2004)

Data Source	Example
Historical Records	diagrams, schematics, schedules
Observations	time studies, walkthroughs
Interviews	discussion of process steps
Process Owner/Vendor Estimates	process time estimates

The data for this study was collected through interviews and questionnaires sent to process owners and facilitative sessions with industry experts. Initially, the interviews were used to discuss the main process steps and build the current situation process map. Then, as the main objective is to map a future RSC for EV batteries that does not exist, this study relies on process owner estimations based on their experience working in pilots for EoL EV batteries. The participants of this study were managers and directors from a scrap car recycling company that manages an important ATF network, a remanufacturing company, a repurposing company, and a lithium-ion battery recycler. In a section of the interviews, the interviewees were asked about the correspondent processes routing involved in the EoL management of electric vehicle batteries. Meanwhile, the questionnaires were used to collect specific data for the simulation model, such as processing times of each of the activities, sequences, and workforce schedules.

To complement the initial data collected, facilitative modelling sessions are conducted with participants from five additional companies with wide knowledge about the different EOL processes and experience working on EoL EV battery projects and pilots. The companies selected for the facilitative session are Client_AC - Automotive company, Client_RG -Recycling group, Client_EC- Engineering company, Client_CF- Consultancy Firm specialised in lithium-ion battery and electric vehicle supply chain, Client_CF2- Consultancy Firm specialised in circular economy projects. The facilitated modelling session is used to refine the integrated process map of the RSC for EV batteries and refine processing times and validate the simulation model. Moreover, the participants were identified as potential users of the proposed simulation model.

5.5.4. Verification and validation

Before analysing the simulation model results, its necessary to ensure that the model built gives a valid representation of the system to be studied. To achieve that objective, verification and validation of the simulation model should be conducted. The verification process aims to ensure that the model built using the software is a correct representation of the process map of the system (Greasley, 2004). The structured walkthrough and animation inspection were chosen to do the model verification. The structured walkthrough consists of including the perspective of someone not involved in the model built up. For the walkthrough verification, the researcher explained the steps to build the model to other researchers and academics familiar with Arena Software to identify errors and get new ideas and suggestions. The animation inspection of this study consisted of reducing the simulation's speed to verify that the batteries were moving following the correct sequences. The outcome of the verification was that the entities in the model were following the route sequences correctly.

The validation process, on the other hand, helps to ensure that the model behaviour is similar to the real-world system or to the purposes of the simulation study. The three aspects of validation proposed by Pegden, Shannon and Sadowski (1995) are used: conceptual validity, operational validity, and believability.

Conceptual validity ensures that the model built represents a credible approximation to the real-world system. To confirm the conceptual validity of this simulation model and increase its credibility, discussions and data were collected from this study's participants. The participants of this study have knowledge about the different EoL processes and experience working on EoL EV batteries projects and pilots. The operational validity can be usually confirmed by comparing the results obtained in the model with the real-world performance (Greasley, 2004). In this case study, as the simulation model represents a potential EoL RSC that does not exist, the validation was conducted by conducting a sensitivity analysis of the simulation model subsystems. Banks *et al* (2005) suggest some alternatives to validate the DES model behaviour for systems with no operational or limited historical data. The alternatives suggested by Banks *et al* (2005) are parameter sensitivity test and structural sensitivity test. The parameter sensitivity test consists of testing if the behaviour of the model is sensitive to reasonable variations in the parameter values. The parameter sensitivity was tested by observing how sensitive is the model to the changes by varying factors below and above the initial data of the subsystems in Arena 16.2 simulation software. The structural sensitivity test consists of assessing if the behaviour of the model change with structural variations. For this study the structural sensitivity test was conducted by changing the logical configuration of the simulation system and observing the changes. The third aspect of validation is believability. The believability consists of ensuring that the module outputs of the model are credible for the simulation users. To ensure believability, industry experts from companies and projects that focus on the EoL management of EV batteries were gathered to explain the simulation project objectives, the capabilities of the simulation and assumptions.

5.5.5. Data analysis

A sensitivity analysis of the proposed simulation model is conducted to analyse the simulated experiments. The sensitivity analysis is used to measure the effect of the input parameters of the simulation (Rossetti, 2015). In this case study, the sensitivity analysis is conducted to study the managerial effect of a set of model parameters on the system performance and sustainability of the proposed simulation model. When doing a sensitivity analysis, for each set of experiments one factor or a combination of them can be examined.

The process analyser is a software included in Arena 16.2 to do sensitivity analysis that allows to set up and run batches of several experiments simultaneously. This tool allows the modeller to control the input parameters (e.g. variables, capacities) and define the response variables (e.g. counters and output statistics) for one simulation model (Rossetti, 2015). To do the sensitivity analysis of the UK EV battery EoL reverse supply chain performance, a series of numerical experiments are conducted using process analyser by varying different model parameters of interest e.g. number of resources per facility, arrival rate of batteries, processing times and analysing the effect in output statistics e.g. number of batteries processed, resources utilisation.

5.6. Ethical considerations

Following the commonly agreed university ethics standards of data protection, confidentiality and anonymity, the name of the companies and participants of the case study will not be mentioned in this research to maintain the confidentiality of this research. The data collected from participants will only be used for the development of this case study. The participants will be contacted through e-mail. Before the video-call interviews with the leaders, managers and directors of the participant companies, they will receive a participant's consent form. The consent forms will include a brief description of the research project, the purpose of the interview, the length of time the data will be stored and how the data is planned to be used. In addition, the consent form will emphasise in writing that participation is voluntary and that the interviewee can withdraw from the study at any time. The identity of participants will remain anonymous, and any detail that would allow the person to be identified will not be published. Volunteers will also have the right to request any data stored related to them, such as the interview transcript. The approved consent forms will be stored with the data collected for five years. Only participants, the researcher, supervisors, and examiners will have access to the data of this research (interview transcripts and questionnaires responses and company records). The findings of the study will be included in the thesis document, and a copy will be shared with the participants. Participants will receive a copy of the transcript and findings. All the information included in the findings will be anonymised. The name of the companies and participants of the study will be anonymised, and it will not be possible to recognise the company or the participants by their description in the findings documents and thesis. Finally, the company data and interview transcripts will be secured using password access, and only the researcher and supervisor will have access to such files.

6. Findings from case studies in the UK EoL RSC EV batteries

6.1. Introduction

This research presents a multiple case study in the context of the UK end-of-life RSC supply chain for electric vehicle batteries. The unit of analysis is the EoL RSC for EV batteries which is in a emerging stage. Some of the few returning batteries currently under warranty are returned through Dealer Service Centres. A dealer service centre is where car users take their vehicles for maintenance or repair when the vehicle is under warranty. Dealers are sending back these batteries to EV manufacturers. A few EV companies like Nissan, Honda, Toyota and Volkswagen are running pilots with remanufacturing companies to evaluate the possibility of remanufacturing and refurbishing their batteries. In the case of the vehicles out of the guarantee period or if the car owner wants to get rid of their EV, EV users can sell their cars to Scrap Car recycling companies that will send the EV to an ATF (Authorised Treatment Facility) for battery removal and dismantling. An ATF is a vehicle dismantler who has proved it follows strict EoL vehicle (ELV) guidelines that are monitored by the Environment Agency (EA). Some ATFs request scrap car recycling companies to handle the batteries, sending them to an Approved Battery Exporter (ABE) with the authorisation to export automotive batteries. To this date, there are not many established recycling facilities processing electric vehicle batteries in the UK.

For this reason, most of the electric vehicle batteries that need to be recycled are exported to mainland Europe, adding logistic costs and carbon footprint. However, the UK scenario is changing, and there is a growing interest in establishing UK-based recycling facilities. Some UK-based recyclers are about to open new facilities specialised in recycling lithium-ion batteries from electronic devices and electric vehicles. After recovering the batteries materials, recyclers would sell the recovered material to different recycling companies depending on the material type.

The map of the UK EoL supply chain for electric vehicle batteries with the companies that participated in the initial part of the case study, **highlighted in bold**, may be seen in Figure 6.1. This supply chain represents the current and potential routes that batteries could follow at the end of their life.

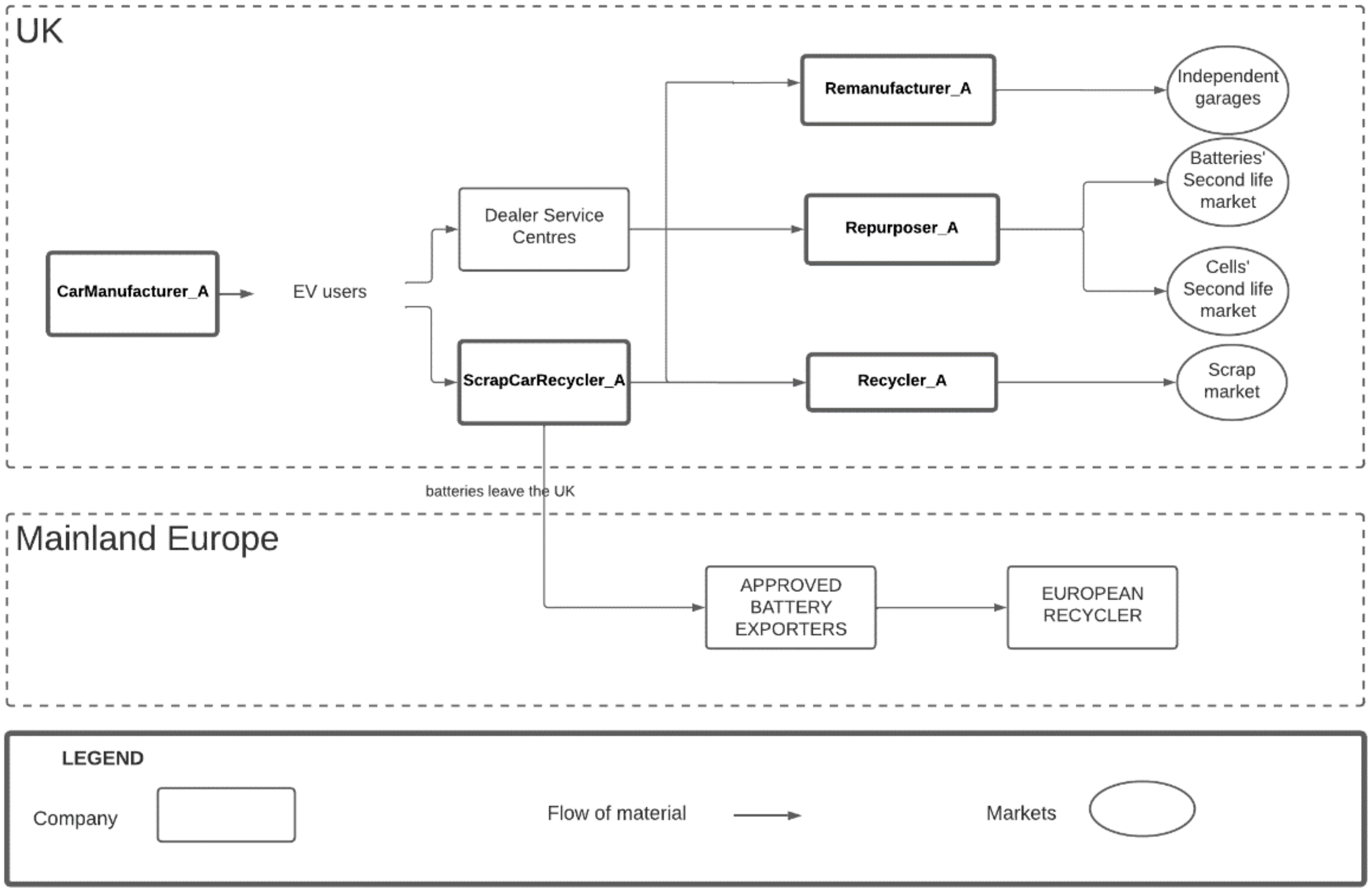


Figure 6.1 UK EOL supply chain for electric vehicle batteries

The findings of each of the case studies are going to be structured following the Framework (See Figure 6.2) explained in **Chapter 4. Conceptual Framework**

Figure 6.2.The general Framework for the analysis of findings

6.2. Case study 1 - Remanufacturer_A

6.2.1. Company background

Remanufacturer_A is a specialist in sustainable engineering solutions with expertise in the electric vehicle industry. Remanufacturer_A is a former division of ICE_Reman_A. ICE_Reman_A has over 50 years of experience in remanufacturing manual transmission, petrol & diesel engines and transfer boxes from the automotive industry. Remanufacturer_A aims to extend its expertise into the manufacture and remanufacture of zero-emissions products that contribute to the UK manufacturing, UK supply chain and UK project partners with innovative products that benefit the environment. Remanufacturer_A offers a wide range of circular economy solutions, and some of the projects that they have developed recently that involved electric batteries are the following:

Disassembling for recycling purposes: Remanufacturer_A has wide experience working on projects for major OEMs, and they are developing specialised EV battery programs for automotive manufacturers, Authorised Treatment facilities and transport companies. Remanufacturer_A has already run some pilots with UK companies. In one of the pilots, Remanufacturer_A received 12 batteries from one of its clients that needed to be taken apart for recycling. As Director_Reman_A explained, recycling gives the lowest return on revenue from all the value recovery options for batteries. However, Director_Reman_A suggested, *"We actually could not, unfortunately, use the modules within these batteries for second-life applications because that was down to our customer preference".*

Refurbishing feasibility: Remanufacturer_A also worked on a refurbishment project for a UK cab company, Taxi_A. Taxi_A asked Remanufacturer_A to develop an EV battery aftermarket strategy for them. The refurbishing project was important for the aftermarket needs of Taxi_A since its battery warranty for the EVs bought in 2017 ended in 2022. The project aimed to demonstrate that Taxi_A could save in EoL battery treatment out of the warranty period by refurbishing their batteries. The refurbishment strategy consisted of exchanging modules of Taxi_A EV batteries that have suffered degradation for usable modules with life in them. The refurbished batteries could then go back into the Taxi_A vehicles but with less warranty period that could vary between twelve and eighteen months.

Remanufacturing feasibility: Director_Reman_A mentioned that other clients brought their electric vehicle batteries to identify if they could be remanufactured. To answer that question, Remanufacturer_A had to identify the best way to take the battery apart, ensure that the process was not destructive, and identify the hazards associated with dismantling.

Through these projects, Remanufacturer_A aims to demonstrate to companies from a business model perspective that there is also value in remanufacturing and refurbishing if the battery design allows it.

6.2.2. Drivers and barriers for implementation of environmental strategies

Drivers

Remanufacturer_A is a company with vast experience working directly with OEMs. When Remanufacturer_A was a division of ICE_Reman_A, they remanufactured and repaired ICE (Internal Combustion Engine) from OEM vehicles under a warranty period. Since the remanufacturing and repairing business was not constant and had some peaks and throughs, the company set up a division to expand the service range and look for new potential customers.

The analysis of the interview with Director_Reman_A suggested that one of the main drivers for Remanufacturing_A to start offering specialised EV battery remanufacturing services were the changes in legislation, automotive industry evolution and market expansion. As Director_Reman_A suggested, *"We noticed that the legislations*[1] *about*

[1] The European Union battery Directive 2006/66/EC on batteries and waste batteries prohibits the disposal and incineration of all types of batteries, including lithium-ion batteries, delimits manufacturers' responsibilities and sets recycling targets (European Commission, 2013)

the EoL management of vehicles were changing …more companies started producing electric vehicles[2]*, so we asked the engineers to learn about the electrical part of the vehicles"*. Director_Reman_A stated, *"there was an opportunity for the business to make use of our experience offering remanufacturing services… but this time for electric vehicle batteries*." Director_Reman_A argued that there is an unattended market that is expected to grow significantly in the following years. As he said, *"the remanufacturing work of electric vehicle batteries in the UK is still in its infancy… we are looking for opportunities to develop electric vehicle battery programs for the major OEMs"*.

According to the interview findings, no UK remanufacturing companies have contracts with car manufacturers or dealers. According to Director_Reman_A, the volumes of EoL electric vehicle batteries are still low and will remain like that for the next three or four years. As the interviewee suggested, *"there is an opportunity for companies like ours to build a road map to extend the life of batteries since this could be a valuable business opportunity"* (Director_Reman_A). Even though high volumes of returned batteries are not expected before the following years, Director_Reman_A argues that OEMs could get prepared downstream in advance to process the future high volumes.

Barriers

A couple of interesting findings of the interviews with Director_Reman_A, were that the main barriers to remanufacturing EV batteries are the limited information that remanufacturing companies have about the internal design of batteries and their ideal performance. Director_Reman_A suggested that on some occasions, his company receive batteries from business clients or Authorised Treatment Facilities (ATFs) categorised as "black boxes". According to Director_Reman_A, "*batteries are classified as black boxes when EV manufacturers do not have access to any information for handling, disassembling, measuring the state of health of batteries or recovering their value"*. As Director_Reman_A explained, *"they (battery manufacturers) won't share their information about the batteries, and that starts to impact on our understanding... when a client wants you to do something with the battery, but there's no knowledge about its performance, it makes our job more difficult".* Director_Reman_A suggested, *"without the information about battery design, the disassembly process could take hours and can even damage the battery and components internally due to incorrect manipulation*". Moreover, he considers that establishing the state of health of batteries (SOH) becomes complicated when they do not have the performance information of a new battery (i.e. SOH=100%). According to Director_Reman_A, *"the next best thing to do is get a brand*

[2] EV sales worldwide exceeded two million in 2019 which represented an increase of 15% compared to 2018 (Deloitte LLP, 2019).

new battery and use that as a master and do it all the benchmark between the good battery and the one that you've you received". As Director_Reman_A explained, they need to follow this benchmarking process (i.e. new battery vs. old battery) for each type of battery received since the configuration and design of batteries may vary significantly depending on the chemistry, car brand and model. According to Director_Reman_A, *"measuring the SOH of batteries is more of a scientific guess rather than an accurate measurement."*

Director_Reman_A also suggested that the current legislation is not promoting remanufacturing. According to Director_Reman_A, *"if EV battery manufacturers do not share information about the design, internal characteristics and content of batteries, legislations could force them to do it"*. Director_Reman_A argued, *"if we could get easier access to the battery information directly from designers, we would be able to do harmonious (remanufacturing) work like the one done with engines and gearboxes from most of the UK OEMs."* As the interviewee suggests, *"the more legislation is put on battery manufacturers to be able to share information, the better will be to handle and recover more value from batteries."*

Table 6.1 shows drivers and barriers to the implementation of sustainability strategies in the EoL EV battery industry. The representative quotations for the drivers and barriers are summarised in Table 6.1. The quotations are organised by the aggregate dimension, first-order themes and second-order themes. The categories for the aggregate dimensions and second-order themes are "a priori" extracted from previous literature (Govindan and Bouzon, 2018; Govindan and Hasanagic, 2018; Narimissa, Kangarani-Farahani and Molla-Alizadeh-Zavardehi, 2020) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** In contrast, the first order themes were derived from the findings.

Table 6.1. Drivers and barriers for the implementation of environmental strategies in the EoL EV battery industry (Author, 2024)

Aggregate dimension	Second-order theme	First-order theme	Representative quotations
Drivers for the implementation of sustainability strategies	Policy	EoL management legislations	*"We noticed that the legislations about the EoL management of vehicles were changing."*
	Market and competition	Industry evolution	*"more companies started producing electric vehicles, so we asked the engineers to learn about the electrical part of the vehicles."*
		Business opportunity	*"the remanufacturing work of electric vehicle batteries in the UK is still in its infancy… we are looking for opportunities to develop electric vehicle battery programs for the major OEMs"*
		Competitive advantage potential	*"there is an opportunity for companies like ours to build a road map to extend the life of batteries since this could be a valuable business opportunity"*
	Knowledge	Operational capabilities	*"there was an opportunity for the business to make use of our experience offering remanufacturing services ….but this time for electric vehicle batteries"*

Aggregate dimension	Second-order theme	First-order theme	Representative quotations
Barriers for the implementation of sustainability strategies	Knowledge	Lack of information flow	-*“without the information about battery design, the disassembly process could take hours and can even damage the battery and components internally due to incorrect manipulation*” - *“measuring the SOH of batteries is more of a scientific guess rather than an accurate measurement.”*
	Policy	EoL management legislations	*“the more legislation is put on battery manufacturers to be able to share information, the better will be to handle and recover more value from batteries”*

6.2.3. EoL Reverse supply chain elements

Processes

The analysis of the interview with Director_Reman_A suggests that the processes followed by Remanufacturer_A to process EV batteries are the ones described below.

When Remanufacturer_A receives EV batteries from their clients, they need to check if the cooler pipes have come loose or split within the pack because they could cause a shortcut. Then, the diagnosis of the state of health of the batteries (SOH) can be conducted. As Director_Reman_A mentioned, estimating the SOH of an EV battery is a complex process which is not required for gearboxes and engines. The testing of EV batteries is a key step to identifying what the faults are and, based on that information, deciding where to send the batteries. An important finding of this case study is that no single testing process can be applied to all EV batteries. As Director_Reman_A indicated, the testing of batteries is not a straightforward process. Director_Reman_A explained, "*it's not one test ....it will be multiple tests that need to be designed ...to be flexible to be able to cheque a CarBrand_A or CarBrand_B battery or a CarBrand_C one.* The analysis of the interview suggests that Remanufacturer_A needs to make its testing process flexible enough because, as Director_Reman_A argued, *"we can't have a test line for every type of battery because that is not financially viable.... it is a multifaceted test that we require."*

Remanufacturer_A has identified three possible routes with three separate lines for the batteries. The first line is for the batteries that are not good to use. In this first case, batteries can be dismantled to a module level and prepared for recycling. The parts that can still be reused would be kept at the facility.

The second option for batteries is harvesting. Harvesting in this context refers to gathering the useful parts of products to store them and use them later for remanufacturing. For instance, *"if there is a battery with 18 modules and one string of 6 modules is fine, and the other two strings are broken, the good string with six modules combined with other useful parts could be used to build a full battery again"* (Director_Reman_A). Finally, the third route would be for good functional batteries that can be refurbished or remanufactured by exchanging the modules and cells. The analysis of the interviews suggests that the batteries must be disassembled to a module or cell level for any of the three routes.

An interesting finding from the interview with Director_Reman_A is that the remanufacturing option would only be economically viable if the design of the battery allows a non-destructive disassembly. Director_Reman_A explained, *"we need to go through the process of working out how I would take it (the battery) apart and identifying safety risks … if the design would need to change because we get to a point where it doesn't become an easy disassembly, it becomes a destructive disassembly".*

The representative quotations for the processes are summarised in Table 6.2. The quotations are organised by the aggregate dimension, first-order themes and second-order themes. The categories for the aggregate dimensions and second-order themes are "a priori" extracted from previous literature (Fleischmann, Ronald and Dekker, 2000) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** In contrast, the first-order themes were derived from the findings.

Table 6.2. Requirements of the process in the EoL EV battery industry (Author, 2024)

Aggregate dimension	Second-order theme	First-order theme	Representative quotations
Process	Testing	Flexibility	*"it's not one test ...... will be multiple tests that need to be designed "*
	Disassembling	Planning	*“We need to go through the process of working out how I would take it (the battery) apart and identifying safety risks … we get to a point where … it becomes a destructive disassembly.”*

Relationship

The analysis of the interviews suggests that the relationships between Remanufacturer_A and car manufacturers are mainly transactional. According to Director_Reman_A, *“ we have worked in pilots with two UK car manufacturers but does not have any contract or agreement in place for remanufacturing or refurbishing batteries”.* Director_Reman_A indicated, *"I do not know anybody (remanufacturer) at the moment in the UK that has got contracts awarded”.* Director_Reman_A mentioned that, as the volumes of returning batteries are still low, it is unusual for car remanufacturers to get involved and sign contracts at this early stage. However, as he explained*, “it would be beneficial for the companies downstream if they could start building relationships at this early stage to be prepared for the volumes coming in the next years by setting up facilities and preparing solutions according to the client’s needs”.*

Director_Reman_A considers that car manufacturers will keep paying recyclers to take the modules and cells to recover the value of materials in the short term. However, he suggested that *“in the future, recyclers will get enough revenue from selling high volumes of exotic battery materials such as cobalt and nickel back to the mining industry or back to the battery manufacturers”.*

The representative quotations for the relationships are summarised in Table 6.3. The quotations are organised by the aggregate dimension, first-order themes and second-order themes. The categories for the aggregate dimensions and second-order themes are "a priori" extracted from previous literature (Lambert, Emmelhainz and Gardner, 1996) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** In contrast, the first-order themes were derived from the findings.

Table 6.3. Relationships between focal company and other EV battery supply chain actors (Author, 2024)

Aggregate dimension	**Second-order theme**	**First-order theme**	**Representative quotations**
Relationships with EV battery supply chain actors	Arm's length	Lack of contracts	*"we have worked in pilots with two UK car manufacturers but does not have any contract or agreement in place for remanufacturing or refurbishing batteries".*
	Absence of relationship	Need of partnership	*"it would be beneficial for the companies downstream if they could start building relationships (with car manufacturers) at this early stage to be prepared for the volumes coming in the next years by setting up facilities and preparing solutions according to the client's needs".*

6.2.4. Sustainable EoL Reverse supply chain

Sustainable supply chain strategies

The analysis of the interviews suggested that the feasibility analysis of remanufacturing and refurbishment of "black boxes" becomes more difficult because the disassembly process may turn destructive, and the SOH assessment may be inaccurate. Therefore, the value recovered from an EV battery may be lower.

A sustainability strategy identified from the interviews with Director_Reman_A was the collaboration of Remanufacturer_A with battery manufacturers. As Director_Reman_A argued, *"a battery made in the UK ... that is a perfect scenario for remanufacturing* *because ... you can get easier access to the designers and ...producers of the batteries to work together".* The interview findings suggest that a closer collaboration between battery producers and remanufacturers within the UK could help to improve the Disassembly process (faster and less destructive), and SOH assessment (faster and more precise) to extend the lifespan of batteries, modules and components. Consequently, improve the environmental and economic impact of the EoL management of batteries in their RSC.

Another interesting sustainability strategy identified in the interviews with Director_Reman_A is the interest of Remanufacturer_A to do a logistical integration with recycling companies. According to Director_Reman_A, the company plans *"to set up a facility (remanufacturing facility) inside a recycling facility so basically, the waste (of the remanufacturing process) can go straight to the recyclers".* As Director_Reman_A suggests, "*remanufacturers will always end up with materials that cannot be used for harvesting or remanufacturing, and the only option is to send them for recycling"*. The interview findings suggest that by having a remanufacturing facility inside a recycling facility, the waste material can go straight to the recyclers and reduce the time spent moving the batteries, hazard risks and the operational and transport cost associated.

Director_Reman_A explained another sustainability strategy related to a business model shift. The interview findings suggest that Remanufacturer_A is trying to demonstrate that there is enough value in remanufacturing and repurposing to shift their business model. As Director_Reman_A explained, *"manufacturers have to pay to have the battery taken away... if we get the volumes we could tell the customers... if we did A, B, C with your batteries and we were able to pay you X pounds so we could use them (components) for middle applications."* Director_Reman_A suggested that in the future EV manufacturers may not need to pay for their EV batteries to be taken away because the expenses of processing high volumes of EoL EV batteries could be covered by the sales of remanufactured/repurposed batteries, repurposed and recycled modules, cells and materials.

The analysis of the interview suggests that Remanufacturer_A is looking to collaborate with EV battery material recyclers. According to Director_Reman_A, the recycling businesses are only profitable with high volumes of material. However, Director_Reman_A explained that they probably would not receive enough volumes of batteries to get economies of scale in the next five years. As Director_Reman_A suggests, *"we are trying to work with recyclers from the off and then trying to get as many* *battery products (that they cannot use for remanufacturing/refurbishing) in to help them get the volume."*

The interview findings suggest that Remanufacturer_A has not worked directly with Authorised Treatment Facilities (ATFs) yet but is looking forward to doing it in the future. In the past, Remanufacturer_A has only had automotive OEMs as clients since these companies hired Remanufacturer_A to collect their scrapped waste (e.g. scraped engines and gearboxes). However, Director_Reman_A thinks the scenario will be different in the EoL EV batteries business. As Director_Reman_A stated, *"ATFs are aware that they are going to end up receiving volumes of EV batteries in the next years, so companies like Remanufacturer_A and recyclers could capture the volumes of batteries they need from them"*. For this reason, Director_Reman_A explained that Remanufacturer_A is trying to engage with ATFs in an early stage. Director_Reman_A argued, *"the relationship with the ATFs is absolutely really key in this instance".* The interview analysis suggests that collaborating with ATFs could help Remanufacturer_A and their material recycling partners capture as many batteries as possible from the market and get the volumes they need to make their business profitable.

The representative quotations for the sustainability strategies are summarised in Table 6.4. The quotations are organised by the aggregate dimension, first-order themes and second-order themes. The categories for the aggregate dimensions and second-order themes are "a priori" extracted from previous literature (Beske, Land and Seuring, 2014) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** In contrast, the first-order themes were derived from the findings.

Table 6.4. Future sustainability strategies (Author, 2024)

Aggregate dimension	**Second-order theme**	**First-order theme**	**Representative quotations**
Sustainability strategy	Collaboration	Enhanced communication	*"a battery made in the UK ... that is a perfect scenario for remanufacturing because ... you can get easier access to the designers and ...producers of the batteries work together... and that is ..harmonious."* (Director_Reman_A)
		Logistical integration	*"to set up a facility inside a recycling facility so basically the waste (of the remanufacturing process) can go straight to the recyclers."* (Director_Reman_A)
	Innovation	Business model	*"manufacturers have to pay to have the battery taken .. if we get the volumes we could tell the customers... if we did ABC with your batteries and we were able to pay you X pounds so we could use them (components) for middle applications"* (Director_Reman_A)
	Partnership building	Long-term relationship	*"trying to work with recyclers from the off and then trying to get as many battery products in to help them get the volume "* (Director_Reman_A)
		Long-term relationship	*"the relationship with the ATFs is absolutely really key in this instance"* (Director_Reman_A)

6.3. Case study 2 – ScrapCarRecycler_A

6.3.1. Company background

ScrapCarRecycler_A offers vehicle scraping services to car manufacturers and general vehicle users and supports vehicle manufacturers in meeting their target obligations for recycled materials from end-of-life vehicles. The scrap car recycling analysed in this study has UK's largest scrap car recycling network. ScrapCarRecycler_A has contracts with a network of Authorised Treatment Facilities (ATFs)[3] to provide the nationwide coverage that vehicle manufacturers and car owners need. Moreover, the company offers its clients free scrap car collection and supports clients in sorting the DVLA (Driver and Vehicle Licensing Agency) paperwork. ScrapCarRecycler_A has wide experience processing ICE vehicles, and during the last few years, the company has started processing EVs.

As Manager_SCR suggested, *"we (*ScrapCarRecycler_A*) help vehicle manufacturers to meet their target obligations for recycled materials from end-of-life vehicles".* ScrapCarRecycler_A offers scrap car recycling services to car manufacturers that produce EVs. ScrapCarRecycler_A has some of the largest car manufacturers that dominate the EV market as clients. Although, as Manager_SCR suggests, they have noticed that the number of EV vehicles from pure EV manufacturers is increasing. ScrapCarRecycler_A also offers scraping services directly to the public. ScrapCarRecycler_A is responsible for arranging the vehicle collection, de-pollution and dismantling through its ATF network. Moreover, after the vehicles are dismantled and scrapped at the ATFs, ScrapCarRecycler_A ensures that the vehicles' scraped parts are sent to one of its material recycling partners.

6.3.2. Drivers and barriers for implementation of environmental strategies

Drivers

Manager_SCR argued that the changes in the market had been the main driver that forced them to adapt their business to the automotive electrification needs. According to Manager_SCR , *"electric vehicles are an interesting change in the (automotive) market really.... we see it is small change now but .... I think that the landscape is going to change our business".* ScrapCarRecycler_A has received a few EVs from clients over the last few years. However, as Manager_SCR suggested, the expected increase in the number of electric vehicles entering the market is making ScrapCarRecycler_A adapt their processes, services, and business model to that focused mainly on ICE vehicles.

[3] An ATF is a scrap car facility that has proved it follows the strict End of Life Vehicle (ELV) guidelines and is licensed by the Environment Agency (EA).

Barriers

According to the interview findings, one of the main barriers that ScrapCarRecycler_A faced when receiving EVs is related to the ATF's operational labour skills. As Manager_SCR suggested, *"one of the issues is unfamiliarity (with EVs and EV batteries). So you know if they (ATF operators) have not been trained on them (EV batteries) … some authorised treatment facilities do not even want to touch them."* Infrastructure was highlighted by Manager_SCR as another essential barrier to consider in the following years. Manager_SCR explained that the lack of space to manipulate and store the batteries would also be an important issue for ATFs in the future since handling and processing EVs demand large spaces for safe operations. As Manager_SCR suggested, *"you do need specific space away from other vehicles …. and some of these sites are in city centres you know they are on very tight sites …. that's a problem for them some of the sites."* Manager_SCR indicated that ATFs might need to start looking for bigger spaces to set up their facilities in the future if they want to receive EVs. According to the interview findings, the high battery export costs are another critical barrier that ScrapCarRecycler_A faces in dealing with EV batteries. Manager_SCR explained, *"we are able to get them (batteries) properly recycled, but currently that means exporting them over to mainland Europe... since the advent of Brexit, it's become even more difficult, more expensive, unfortunately"*.

The representative quotations for the drivers and barriers are summarised in Table 6.5. The quotations are organised by the aggregate dimension, first-order themes and second-order themes. The categories for the aggregate dimensions and second-order themes are "a priori" extracted from previous literature (Govindan and Bouzon, 2018; Govindan and Hasanagic, 2018; Narimissa, Kangarani-Farahani and Molla-Alizadeh-Zavardehi, 2020) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** In contrast, the first-order themes were derived from the findings.

Table 6.5. Drivers and barriers for the implementation of environmental strategies in the EoL EV battery industry (Author, 2024)

Aggregate dimension	**Second-order theme**	**First-order theme**	**Representative quotations**
Drivers for the implementation of sustainability strategies	Market and competition	Industry evolution	*"electric vehicles are an interesting change in the (automotive) market really.... we see it is small change at the moment but ..... I think that the landscape is going to change our business"* (Manager_SCR)
Barriers for the implementation of sustainability strategies	Technology and infrastructure	Technically skilled labour	*"one of the issues is being unfamiliarity. So you know if they haven't been trained on them you know some authorised treatment facilities don't want to touch them"* (Manager_SCR)
		Infrastructure investment	*"you do need specific space away from other vehicles …. and some of these sites are in city centres you know they are on very tight sites …. that's a problem for them some of the sites."* (Manager_SCR)
	Economy	Operational cost	*"we are able to get them (batteries) properly recycled, but currently that means exporting them over to mainland Europe... since the advent of Brexit, it's become even more difficult, more expensive, unfortunately”*. (Manager_SCR)

6.3.3. EoL Reverse supply chain elements

Processes

The analysis of the interview with Manager_SCR suggests that the process flow followed by ScrapCarRecycler_A to process EVs and EV batteries are the ones described lines below.

ScrapCarRecycler_A receive vehicles from two different types of clients, car manufacturers and EV owners. The vehicles can be referred by EV companies and Dealers that publicise in their web page that ScrapCarRecycler_A is their EoL vehicle partner. For instance, if a person owns a car from OEM_A that has a contract with ScrapCarRecycler_A, he can enter to OEM_A website, look for the environmental section and follow the links and then end up on the particular landing page of ScrapCarRecycler_A for OEM_A vehicles so ScrapCarRecycler_A can arrange the next steps. The other group of clients that are the general car owner; the potential clients can get a quotation through ScrapCarRecycler_A's website or its customer line. Then, if the quote is accepted, ScrapCarRecycler_A will refer the vehicle to the nearest ATF of their network.

When ScrapCarRecycler_A accepts an electric vehicle from one of its customers, they send a driver to collect the vehicle with all the relevant vehicle information. Before uplifting the car, the driver sent by ScrapCarRecycler_A must visually inspect the car to verify that it is safe to collect and has no dangerous damage. The responsible for the collection ensure to send the electric car to the closest ATF that must be prepared to handle this type of vehicle.

According to Manager_SCR, an important requirement to process EVs demands is the investment in equipment and facilities. Regarding the equipment requirements, Manager_SCR said, *"instead of four post ramps capable of supporting hefty vehicles, ATFs need a simpler two-post ramp to access the battery underneath the (EV) car"*. Moreover, Manager_SCR suggested that the ATFs also need *"insulated tools and personal protective equipment.. and undercovered facilities to work and the proper storage space for the batteries and racking"*.

Once the vehicle arrives at the yard, the ATF workers should do another inspection to check that nothing happened to the EV while in the transport. Then, depending on the vehicles' conditions, they will need to drain the battery coolant before moving to the next step.

A particular requirement for disassembling EVs that is unnecessary for ICE vehicles is to follow the IDIS (International Dismantling Information System)[4] for safe EV battery removal. Manager_SCR explained that disassembling an EV requires significant time since it is not a standard process and requires carefully reviewing specific guidelines. As Manager_SCR said, *"going through the IDIS procedure to make that battery safe to remove…..going through those steps very carefully and methodically adds a lot of time on to that (dismantling) process"*. As Manager_SCR suggested, there is a different procedure depending on the EV brand and model. Hence, it is important to follow carefully the instructions specified in IDIS to work correctly and safely with electric vehicle batteries. According to Manager_SCR, "*even though IDIS has valuable information, it becomes complicated for operators to scroll through IDIS guidelines while manipulating the batteries*". For that reason, ScrapCarRecycler_A has recommended that ATFs print the information to make it easier to review, but it is still the most time-consuming activity. Besides the information found in IDIS, operators should follow the steps learnt at their previous training.

Then, the EV is put on the ramps, batteries are isolated, and any coolant is drained from it. Later, the operators can disconnect the battery from the car and remove the safety plug, so the battery is safe to handle. Afterwards, the worker should get the battery from the vehicle using the right lifting equipment, and any exposed connexions or sockets should be taped. Later, they should put the battery under a high-voltage rubber mat in a safe undercover area with plenty of ventilation. The operator should also put a sign on the battery saying it is high voltage. Once the electric battery is safe, the vehicle is depolluted and dismantled as any regular vehicle.

The representative quotations for the process requirements are summarised in Table 6.6. The quotations are organised by aggregate dimension, first-order themes and second-order themes. The categories for the aggregate dimensions and second-order themes are "a priori" extracted from previous literature (Fleischmann, Ronald and Dekker, 2000) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** The first-order themes were derived from the findings.

Table 6.6. Requirements of the process in the EoL EV battery industry (Author, 2024)

Aggregate dimension	Second-order theme	First-order theme	Representative quotations

[4] The IDIS is a central repository of manufacturer compiled treatment information for ELVs, with information gathered from manufacturers from Europe, Japan, Korea, Malaysia, India, China and the USA.

Process	Dismantling	Long processing time	*"going through the IDIS procedure to make that battery safe to remove…..going through those steps very carefully and methodically adds a lot of time to that (dismantling) process"* (Manager_SCR)
		Equipment acquisition	*"they've got to re-invest in new equipment.. two-post ramps to access the battery underneath the car."* (Manager_SCR)
			"ATFs also need insulated tools and personal protective equipment." (Manager_SCR)
		Facility adaptation	*"under covered facilities to work and the proper storage space for the batteries and racking."* (Manager_SCR)

Relationships

Regarding the supply chain relationships, according to the interview findings, ScrapCarRecycler_A has three important groups of strategic partners to handle EVs and its correspondent EV batteries: ATFs, British Metals Recyclers Association, and Approved Battery Exporters (ABE).

The interview findings suggest that ScrapCarRecycler_A has a close relationship with its ATF network and is compromised to keep educating them. ScrapCarRecycler_A has in total around 300 ATFs locations across the UK. As Manager_SCR suggested, *"we don't own the authorised treatment facilities, but we have contracts with the biggest network in the UK basically".* When the interview took place, ScrapCarRecycler_A had between 15 and 20 ATFs of the total 300 ATFs that were capable of processing electric vehicles. However, according to Manager_SCR, the number of ATFs that process EVs is expected to grow due to future training courses. As Manager_SCR suggested, *" we have trained ATFs in our network ... to safely dismantle the vehicles ...isolate... and remove the batteries".* Manager_SCR indicated that ScrapCarRecycler_A is sharing relevant information with their ATFs about how to proceed when receiving EVs since the disassembly and treatment of EVs at an ATF differ from the one followed with ICE vehicles. As Manager_SCR suggested, *"we help them (ATFs) to make sure they have got the right equipment in place, risk assessments and personal protective equipment"*.

From the point of view of Manager_SCR, the whole business model of ATFs is expected to change dramatically in the following years. Therefore, he said that there are many aspects that ATFs need to start considering for the unstoppable shift to electric vehicles. Even though most of the cars ATFs are currently receiving are internal combustion engine cars, according to Manager_SCR, some ATFs have already internalised that their business models will change significantly in the future. Manager_SCR argued that some ATFs are even more forward-thinking than others. As Manager_SCR said, ScrapCarRecycler_A's biggest ATF is investing in developing a new exclusive site for EVs. Manager_SCR indicated that ScrapCarRecycler_A is working closely with this ATF to offer them support and guidance.

ScrapCarRecycler_A also has partnered with the British Metals Recyclers Association to offer training courses to the ATFs from their networks. As Manager_SCR suggested, *"we linked up with the British Metals Recyclers Association, and we now offer training courses for ATFs...not only to the ones part of the ScrapCarReycler_A ... they could be part of the British metal recyclers Association network".* Manager_SCR explained that these programs are meant to teach ATFs how to handle electric vehicle batteries.

After the EV batteries are removed from the vehicles, some of them are resold out into the market, which is something that ScrapCarRecycler_A and their vehicle manufacturer clients are trying to prevent. Under the existing Waste Batteries and Accumulators regulations[5], it is not illegal to resell the batteries. However, *"from a safety perspective, and from a control of materials perspective and circular economy perspective, it's not necessarily the best route"* (Manager_SCR). For that purpose, ScrapCarRecycler_A is offering their ATF partners to handle batteries on their behalf to send the batteries to Approved Battery exporters (ABE). As Manager_SCR reported, *"we have agreements in place with companies who are able to export the batteries for recycling".* Manager_SCR indicated that ABEs have the authorisation to export and sell the batteries to battery recyclers in Europe (e.g. SNAM, Umicore) and that these recycling companies are appropriately set up to recycle and recover valuable material from electric vehicle batteries. Manager_SCR explained that every battery that ScrapCarRecycler_A send for recycling through the approved battery exporters follows the corresponding directives and regulations.

The representative quotations for the relationships are summarised in Table 6.7. The quotations are organised by the aggregate dimension, first-order themes and second-

[5] The European Union battery Directive 2006/66/EC on batteries and waste batteries prohibits the disposal and incineration of all types of batteries, including lithium-ion batteries, delimits manufacturers' responsibilities and sets recycling targets (European Commission, 2020)

order themes. The categories for the aggregate dimensions and second-order themes are “a priori” extracted from previous literature (Lambert, Emmelhainz and Gardner, 1996) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** The first-order themes were derived from the findings.

Table 6.7. Relationships between focal company and other EV battery supply chain actors (Author,2024)

Aggregate dimension	**Second-order theme**	**First-order theme**	**Representative quotations**
Relationship	Partnership Type III	Partnership with ATFs	*“we don't own the authorised treatment facilities but we have contracts with the biggest network in the UK basically...we have trained ATFs in our network ... to safely dismantle the vehicles a...isolate... and remove the batteries"* (Manager_SCR)
	Partnership Type II	Partnership with ABE	*"we have agreements in place with companies who are able to export the batteries for recycling"* (Manager_SCR)
	Partnership Type I	Partnership with British metals recyclers Association	*"we linked up with the British metals recyclers Association, and we now offer training courses for ATFs...not only to the ones part of the ScrapCarReycler_A ... they could be part of the British metal recyclers Association network"*(Manager_SCR)

6.3.4. Sustainable EoL Reverse supply chain

Sustainable supply chain strategies

Regarding sustainability strategies, according to Manager_SCR, ScrapCarRecycler_A is *"working (on a project) with companies who will be able to provide the different (EV batteries EoL) strands so that we've got a complete UK-based solution”.* As Manager_SCR argued, this collaboration will help ScrapCarRecycler_A and its partners to bring down the management costs and, hopefully, help with the EV batteries’ circular economy in the UK so the materials will be able to go back into the value chain and be reused.

Manager_SCR explained that the solution proposed by ScrapCarRecycler_A would consist of taking a battery from an ATF, dealer service centre, or manufacturer on authorised transport. Then, the batteries would arrive at a central facility test to identify whether the modules are good for second-life use or should be sent directly for recycling. The other option would be to get those modules repurposed or reused and send the faulty modules for recycling in the UK. For this future project, ScrapCarRecycler_A plans to collaborate with Recyclers and Remanufacturers because setting up recycling, remanufacturing/repurposing facilities demands a significant investment. As Manager_SCR suggested, *"since there are well-established companies already in the market who can do this work and have already made that investment, it makes sense to work with them instead of competing with them". According to* Manager_SCR, ScrapCarRecycler_A has access to what will hopefully be large volumes of electric vehicle batteries in the future. The number of EoL EVs that ScrapCarRecycler_A is processing is currently three figures per annum. Manager_SCR said that from 2018 to 2019, there was a rise of about 40% in the number of EV vehicles processed by the network. In 2020, the number increased by 50% compared to the previous period, and these figures are expected to keep growing. As the companies downstream need that supply, Manager_SCR argued that the collaboration between ScrapCarRecycler_A and recyclers and remanufacturers would be mutually beneficial.

Manager_SCR explained that ScrapCarRecycler_A currently depends on the battery exporter to send the batteries to Europe for recycling. As he suggested, *"currently there are no UK-based recyclers that can safely and responsibly recycle batteries…. However, I say that the answer is a UK-based recycler...that is what we are working towards"* (Manager_SCR). Manager_SCR argued that ScrapCarRecycler_A is looking forward to finding and building a long-term partnership with one UK-based recycler soon to eliminate the cost associated with the batteries export. Manager_SCR said that ScrapCarRecycler_A representatives had had several meetings with UK recycling companies claiming they can recycle electric vehicle batteries. However, the recyclers commonly say that they will be able to do it in the following years. The interviewee argued that they had not found an operating facility offering the material recycling service. However, Manager_SCR indicated that they are optimistic that they will find one UK recycling facility for the batteries soon.

The representative quotations for the sustainability strategy are summarised in Table 6.8. The quotations are organised by the aggregate dimension, first-order themes and second-order themes. The categories for the aggregate dimensions and second-order themes are "a priori" extracted from previous literature (Beske, Land and Seuring, 2014) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** The first order themes were derived from the findings.

Table 6.8. Future sustainability strategies (Author, 2024)

Aggregate dimension	Second-order theme	First-order theme	Representative quotations
Sustainability strategies	Collaboration	New service development	*"we are working with companies who will be able to provide the different strands so that we've got a complete UK-based solution...We would be able to take a battery from an ATF, from a dealership or from a manufacturer ... We would then be able to take the battery ...and transport ... to a central facility test... to get those modules repurposed or reused ...and the faulty modules ... recycled."* (Manager_SCR)
	Partnership building	Partner selection	*"I say that the answer is a UK-based recycler...that is what we are working towards."* (Manager_SCR)

6.4. Case study 3 – Recycler_A

6.4.1. Company background

Recycler_A is a precious metal recovery company that specialises in recovering and processing precious and valuable metals. The company's main business is the metal and catalyst recovery from process and waste chemicals. During the last few years, they have been developing a process for lithium-ion battery recycling, allowing them to spin off their core competencies of treating hazardous chemicals and recovering their metals from waste. Finally, in 2021 Recycler_A opened one of the first UK-based treatment and material recycling facilities for lithium-ion batteries. Recycler_A expects to receive lithium-ion batteries initially from portable devices such as mobile phones and laptops and then electric vehicle batteries.

6.4.2. Drivers and barriers for implementation of environmental strategies

Drivers

The Manager_Recycler_A suggested that the expected future supply was one of the main drivers for Recycler_A to expand its portfolio and to start offering lithium-ion battery recycling services. Manager_Recycler_A reported that Recycler_A directors are convinced that there is going to be enough supply of batteries in the future. As Manager_Recycler_A argued, *"around 2,000,000 vehicles are being scrapped each year. So, if by 2030 there will only be hybrids and electric vehicles and the average life of the battery is, for instance, 15 years, by the year 2045, there will be 2,000,000 vehicles getting scrapped with their corresponding batteries. We have 25 years to prepare to recycle one million tons a year of lithium-ion batteries in the UK."* With this clear vision of the future, Manager_Recycler_A indicated that Recycler_A directors do not want to miss this important business opportunity. Manager_Recycler_A mentioned that the dominant volume of lithium-ion batteries currently comes from portable batteries for mobile phones and laptops, but over time, that will flip to electric vehicle batteries. In the future, according to Manager_Recycler_A, *"(the supply) it is going to be mainly electric vehicle batteries. They are going to be a larger value".*

Another economic driver identified from the interview with Manager_Recycler_A was the potential markets for recovered material (cathode powder, plastic and copper). Manager_Recycler_A suggested that "*the main recovered material is obviously the cathode powder, so that would probably go to…. refiners …. in Europe, South Korea, China …. interested in taking ..nickel and cobalt-rich materials that they could refine."* Another material that could be recovered from batteries is plastic. Moreover, Manager_Recycler_A added, *"for the plastic ….as it is a clean product … any sort of standard plastic recycler should be able to accept that".* Finally, Manager_Recycler_A indicated that copper can also be recovered from batteries, as he said, "*the copper from the anode strips, that could just go to a regular copper metal recycler."* (Manager_Recycler_A).

According to the interview findings, another important driver was the existing metal recovery capabilities of Recycler_A. As Manager_Recycler_A suggested, Recycler_A has "*competencies of dealing with hazardous chemicals doing chemical treatment, physical treatment … recovering their metals from waste".* Manager_Recycler_A argued that Recycler_A used the experience and knowledge acquired recovering metals from waste to develop a process for lithium-ion battery recycling.

Barriers

The interview findings suggest that two of the main barriers to recycling EV batteries are related to the level of operational skilled labour and infrastructure limitations. Currently, operators at Recycler_A cannot receive full lithium-ion batteries from EV vehicles because, as Manager_Recycler_A suggested, "*at the moment, they (operational staff) are not fully trained for high voltage work"*. Manager_Recycler_A explained that Recycler_A operators can only do low-voltage work with a maximum of 150 volts. For that reason, they cannot receive full EV batteries that commonly have 600 volts. In addition, Manager_Recycler_A mentioned, "*we do not have suitable space for doing dismantling or discharging or anything like that".* As Manager_Recycler_A explained, lithium-ion batteries from EVs require wide spaces to operate in a safe way.

According to the interview findings, the limited information about the batteries' modules and cell configuration was another important barrier. As Manager_Recycler_A suggested, "*if there was some information that you could get for example, from the OEM about the bill of materials that would tell you about the chemistry of the cells, that would help…".* Manager_Recycler_A said that the chemistry information is important to separate the modules by chemistry more easily and have a more efficient recycling process.

Moreover, Manager_Recycler_A indicated that "*having some information about how the modules are constructed could be useful, because that would help for dismantling pieces"*. Manager_Recycler_A argued that the information about how the modules and cells are constructed could help to make the dismantling process more manageable and less destructive.

Manager_Recycler_A suggested that the information about chemistry, modules, and cell configuration can be included and shared in a Battery Passport[6]. He mentioned that there have been some discussions in the industry about the implementation of a Battery Passport, and as he said "*it would be interesting to be able to triage them (battery passports) for second life or for recycling."* However, according to Manager_Recycler_A, some confidentiality issues around Battery Passports in the UK need to be addressed before implementing them in the country.

The representative quotations for the drivers and barriers are summarised in Table 6.9. The quotations are organised by the aggregate dimension, first-order themes and second-order themes. The categories for the aggregate dimensions and second-order themes are "a priori" extracted from previous literature (Govindan and Bouzon, 2018;

[6] The Battery Passport is the digital identify of the physical battery that has information about materials origin, battery's chemical composition, manufacturing details, sustainability applications and lifecycle requirements (Goblal Battery Alliance, 2023).

Govindan and Hasanagic, 2018; Narimissa, Kangarani-Farahani and Molla-Alizadeh-Zavardehi, 2020) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** In contrast, the first order themes were derived from the findings.

Table 6.9. Drivers and barriers for the implementation of environmental strategies in the EoL EV battery industry Recycler_A (Author, 2024)

Aggregate dimension	**Second-order theme**	**First-order theme**	**Representative quotations**
Drivers for the implementation of sustainability strategies	Economy	Business Opportunity	*"around 2,000,000 vehicles are being scrapped each year. So, if by 2030 there will only be hybrids and electric vehicles ... we have 25 years to prepare to recycle one million tons a year of lithium-ion battery in the UK."* (Manager_Recycler_A)
		Value recovery	-*"the main recovered material is obviously the cathode powder, so that would probably go to…. refiners …. in Europe, South Korea, China …. interested in taking ..nickel and cobalt-rich materials that they could refine."* (Manager_Recycler_A) - *"for the plastic ….as it is a clean product … any sort of standard plastic recycler should be able to accept that".* (Manager_Recycler_A) -*"the Copper from the anode strips, that could just go to a regular copper metal recycler."* (Manager_Recycler_A)
	Knowledge	Operational capabilities	*"competencies of dealing with hazardous chemicals doing chemical treatment, physical treatment … recovering their metals from waste".* (Manager_Recycler_A)
Barriers for the implementation of sustainability strategies	Technology and infrastructure	Lack of technical skills	*"Our operators at the moment are not fully trained for high voltage work"* (Manager_Recycler_A)

Aggregate dimension	Second-order theme	First-order theme	Representative quotations
	Technology and infrastructure	High infrastructure investment	*"we do not have suitable space for doing dismantling or discharging or anything like that."* (Manager_Recycler_A)
	Knowledge	Lack of information sharing	*"if there was some information that you could get for example from the OEM about the bill of materials that would tell you about the chemistry of the cells…if they are very similar chemistry's, you can put them together.. If not we need to keep them separate ".* -*"having some information about how the modules are constructed could be useful, because that would help for dismantling pieces"* (Manager_Recycler_A)

6.4.3. EoL Reverse supply chain elements

Processes

The process begins by determining if the battery modules need to be discharged. According to Manager_Recycler_A, "*we discharge it, and that could be with the variety of ways you could discharge with some kind of circuits, or you can use, you know, chemical methods*". Then, the next step is the dismantling of modules to cell level. Afterwards, these cells are sent to the recycling facility where the recycling machines are set up. In the recycling facility, the machines start by splitting up the cells. After that, various mechanical and sub-chemical processes separate copper, plastic and cathode powder. As Manager_Recycler_A indicated, Recycler_A expects to recover 80% of the total weight of the batteries.

The interview findings suggested that a particular characteristic of recycling is the long processing times. Manager_Recycler_A argued that "*the most time-consuming activity is dismantling*". Manager_Recycler_A mentioned that working with different types of batteries is time-consuming, and operators must be cautious when dismantling batteries and modules; otherwise, the product may get damaged. As Manager_Recycler_A suggested, "*because you've got to dismantle different types of batteries … you have to use different screw heads... get around things like adhesives... you have got to be really careful with the force that you put on.. or can rip cells open…it just adds complexity and more time to do it".*

At the same time, Manager_Recycler_A argued that dismantling is the most expensive activity. According to Manager_Recycler_A, "*most of the dismantling we do is kind of by hand and tools, that kind of thing to get the cells out"***.** Manager_Recycler_A said that *"dismantling is the most expensive process because, as in most processes, the highest cost is labour, so where your biggest amount of labour goes, that is where your highest cost is".* Manager_Recycler_A explained that *"a lot of the cost comes around from doing it safely so if you had a situation where you could redesign the battery...that would reduce the risks massively and therefore reduce processing costs."* Manager_Recycler_A suggested that battery assemblers and designers could help to improve the recycling process if they considered the disassembly and recycling aspects when designing batteries. As the interviewee indicated, some minor changes in the design, such as the type of adhesive used or removing the cells' welding, may help reduce the processing time and costs significantly.

According to Manager_Recycler_A, the equipment and machines used at the recycling facilities of Recycler_A to process the batteries are not specialised for Lithium-ion batteries. They are generic machines that can be used for different applications. As Manager_Recycler_A explained, "*the individual unit operations are not so specialized for battery recycling, and they could be used for anything, but the way that they've been put together means that they are probably not suitable for anything else."*

Regarding the capacity to process lithium-ion batteries, Manager_Recycler_A suggested that the Recycler_A plant is expecting to have as he said "an *initial capacity of 1000 tons per year working one shift per day"* (Manager_Recycler_A). However, Manager_Recycler_A mentioned that the capacity might be expanded by increasing the hourly work and acquiring new equipment. As Manager_Recycler_A indicated, "*we have a 24-hour licence, we could run 24 hours that's 3000 tons…. we can increase the hours (over weekends) I think to increase the sort of hourly work, but you need to get a larger equipment."*

Regarding the storage facilities, according to Manager_Recycler_A, Recycler_A is expanding its storage capacity to be able to store the recovered material. As Manager_Recycler_A suggested, "*We are expanding our storage capacity… but at the moment, we can probably store, let's say, thirty or forty tons of material.. we're not talking about storing huge quantities at the moment only weeks of stock."* Manager_Recycler_A explained that the warehouse needs to be adapted to store the materials in a safe environment. When asked about the storage space characteristics Manager_Recycler_A said "*it should be covered but it should also be at the least one open side, you don't want like completely enclosed the building so if you have a fire … you don't want that contained in one building because of the risk of building up pressure and breaking the door."*

The representative quotations for the processes are summarised in Table 6.10. The quotations are organised by the aggregate dimension, first-order themes, and second-order themes. The categories for the aggregate dimensions and second-order themes are "a priori" extracted from previous literature (Fleischmann, Ronald and Dekker, 2000) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** In contrast, the first-order themes were derived from the findings.

Table 6.10. Process requirements in the EoL EV battery industry (Author, 2024)

Aggregated dimension	Second-order theme	First-order theme	Representative quotations
Process	Dismantling	Long processing time	*"the most time-consuming activity is dismantling because you've got to dismantle different types of batteries … you have to use different screw heads... get around things like adhesives... you've got to be really careful with the force that you put on.. or can rip cells open…it just adds complexity and more time to do it".* (Manager_Recycler_A)
		Labour intensive	-*"most of the dismantling we do is kind of by hand and tools, that kind of thing to get the cells out".* (Manager_Recycler_A)
		High operational cost	-*"dismantling is the most expensive process because, as in most processes, the highest cost is labour, so where your biggest amount of labour goes, that's where your highest cost is"*(Manager_Recycler_A)

			-*"a lot of the cost comes around from doing it safely, so if you had a situation where you could redesign the battery... that would reduce the risks massively and therefore reduce processing costs"* (Manager_Recycler_A)
	Recovery	Equipment acquisition	*"the individual unit operations are not so specialised for battery recycling, and they could be used for anything, but the way that they've been put together means that they are probably not suitable for anything else."* (Manager_Recycler_A)

Aggregate dimension	**Second-order theme**	**First-order theme**	**Representative quotations**
	Recovery	Flexible capacity	*"initial capacity of 1000 tons per year working one shift per day..we have 24-hour licence, we could run 24 hours that's 3000 tons…. we can increase the hours (over weekends) I think to increase the sort of hourly work, but you need to get larger equipment"* (Manager_Recycler_A)

	Storage	Facility adaptation	*“it (storage area) should be covered, but it should also be at least one open side. You don't want like completely enclosed the building so if you have a fire … you don't want that contained in one building because of the risk of building up pressure and breaking the door”* (Manager_Recycler_A)

Relationships

Regarding the business relationships, at the moment of the interview, Recycler_A did not have any contracts in place with clients for their recycling services. Even though there are no contracts, they have had some promising commercial discussions that make Manager_Recycler_A believes that sooner rather than later, some contracts and deals will be in place. As Manager_Recycler_A suggested, "*we don't have any contracts as such, … there is only a handful of people (recyclers) who do this… let's say a single digit number of companies who have expressed a strong interest to the point of saying you know as soon as your ready we have batteries to give to you".*

Manager_Recycler_A considers that soon OEMs will start recognising the critical role of battery recyclers and the necessity to have partnerships and contracts with them. According to Manager_Recycler_A, car manufacturers do not have to worry about car recycling costs when internal combustion engine (ICE) vehicles need to be scraped. Manager_Recycler_A suggested that "*consumers, according to the legislation, shouldn't pay directly (for recycling). If you take your car for recycling, the recycler will pay you for the car because there is enough value in the car".* As Manager_Recycler_A explained, *"the cost of recycling is paid for by all the value of steel, aluminium, copper and plastic in the car".* Manager_Recycler_A added, *"they (recyclers) will be paying you, for instance, 70 pounds because they will get 100 pounds …if you stick a big battery (EV battery) and then all of a sudden it's a £500 charge to recycle, and now that can't be charged to the consumer".* As Manager_Recycler_A explained that OEMs are responsible for paying that extra cost because of their liabilities. Manager_Recycler_A argued that receiving the bill for recycling a few electric vehicle batteries may not represent too much for OEMs yet; however, when the number of recycled EV batteries starts increasing, the OEMs may start feeling the financial impact. In the future, OEMs, as he said, may "*start setting up contracts with companies (Recyclers, EoL management companies)… to handle all the EV batteries from their vehicles to their vehicles get recycled in the UK .. they will be doing it soon".*

Regarding the relationship with potential clients for the recovered material, Manager_Recycler_A said, *"we've had some communication, but it's been difficult to get any sort of agreements in place because obviously we haven't really got a lot of material to share with people, but we've definitely been discussing it. There are people who showed interest in it"*

The representative quotations for the relationships are summarised in Table 6.11. The quotations are organised by the aggregate dimension, first-order themes and second-order themes. The categories for the aggregate dimensions and second-order themes are "a priori" extracted from previous literature (Lambert, Emmelhainz and Gardner, 1996) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** The first-order themes were derived from the findings.

Table 6.11. Relationships between focal company and other EV battery supply chain actors (Author, 2024)

Aggregate dimension	Second-order theme	First-order theme	Representative quotations
Relationship	Absence of relationship	Lack of contracts	*"we don't have any contracts as such, … there is only a handful of people (recyclers) who do this… let's say a single digit number of companies who have expressed a strong interest to the point of saying you know as soon as your ready we have batteries to give to you".* (Manager_Recycler_A)
	Absence of relationship	Need of partnership	*"they (OEMs) will start setting up contracts with companies (Recyclers, EoL management companies)… to handle all the EV batteries that from their vehicles to get recycled in the UK .. they will be doing it soon".* (Manager_Recycler_A)
	Absence of relationship	Need of partnership	*"we've had some communication (with clients for recovered material), but it's been difficult to get any sort of agreements in place because obviously we haven't really got a lot of material to share with people, but we've definitely been discussing it. There are people who showed interest in it."* (Manager_Recycler_A)

6.4.4. Sustainable EoL Reverse supply chain

Sustainable supply chain strategies

Manager_Recycler_A argues that the EoL management of EV batteries involves different types of activities that require particular skills. Manager_Recycler_A suggested that to keep the business sustainable over time, Recycler_A needs to specialise in a particular activity. As Manager_Recycler_A suggested, *"I just don't want to take on too many things at once … there's various different aspects of this kind of supply … there's the dismantling and discharging ... and chemical material recovery …we've focused on this (chemical material recovery)".* Moreover, he added that might be difficult for one single company to be in charge of all the activities. As Manager_Recycler_A argued, *"I think at the moment for one person to jump in and try and do everything it's just too much.. that you would need to be skilled at so you just got to see where your skills are".*

According to Manager_Recycler_A, in the current business model of recycling companies, their clients pay them to collect and process their batteries since the business is not profitable just from the materials. However, he also suggested that some people in the industry argue that there will be a shift in the business model in the future, and recyclers will start paying for the batteries. From the point of view of Manager_Recycler_A the business model will not change significantly. As he explained, *"I don't see that (business model shift) happening anytime soon. I think the market will drive that as the price is so often".* Manager_Recycler_A argued that he does not see the business model changing because of the expected battery chemistry changes. Manager_Recycler_A explained, *"OEMs and the cell manufacturers are looking at ways of driving down things like cobalt because obviously it has a high cost… a couple of years ago were cobalt price was really high 70-80 dollars a kilo people were paying for the batteries (high cobalt)".* Manager_Recycler_A said that it is possible to reduce processing costs due to economies of scale; however, the business's profitability depends on the value of the recovered material. As Manager_Recycler_A indicated, *"If you got economies of scale and technology to the point that the present costs reduced massively, great, but if you also remove the biggest revenue by the cobalt, then you don't have an awful lot of other revenue in order to offset these processing costs."*

Manager_Recycler_A also suggested that collaborating with other companies is an important strategy to keep their business sustainable in the future. Manager_Recycler_A said that Recycler_A has been in discussions with other companies (Scrap Car recyclers, Remanufacturers, and Repurposing company) involved in the electric vehicle batteries EoL industry to work together and offer EV manufacturers a complete EV battery EoL management solution. Regarding the possibility of collaborating with other companies to offer a full EoL management solution, Manager_Recycler_A suggested, *"we are having those kinds of discussions … I think it's beneficial because it is too much for one* *company to do at the moment given the capabilities that different companies have, I think it makes sense to have people working together, so that you can offer kind of a full service."*

According to Manager_Recycler_A, Recycler_A cannot receive full EV batteries due to capabilities and infrastructure limitations. For this reason, an important partner that Recyler_A requires to process EV batteries is the companies that discharge and dismantle batteries. Manager_Recycler_A said that Recycler_A is interested in working with an upstream company that can do the preliminary discharge and dismantling. As Manager_Recycler_A explained, *"we would prefer to work with someone upstream, someone … that could do the sort of preliminary discharging and dismantling and then give us the modules."*

The representative quotations for the sustainability strategy are summarised in Table 6.12. The quotations are organised by the aggregate dimension, first-order themes and second-order themes. The categories for the aggregate dimensions and second-order themes are "a priori" extracted from previous literature (Beske, Land and Seuring, 2014) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** The first order themes were derived from the findings.

Table 6.12. Future Sustainability strategies Recycler_A (Author, 2024)

Aggregate dimension	**Second-order theme**	**First-order theme**	**Representative quotations**
Sustainability strategies	Innovation	Process specialisation	-*"I just don't want to take on too many things at once … there are various different aspects of this kind of supply … there's the dismantling and discharging ... and chemical material recovery …we've focused on this (chemical material recovery)."* (Manager_Recycler_A) - *"I think at the moment, for one person to jump in and try and do everything, it's just too much.. that you would need to be skilled at, so you just got to see where your skills are."* (Manager_Recycler_A)
		Business model	-*"I don't see that (business model shift) happening anytime soon. I think the market will drive that as the price is so often"* (Manager_Recycler_A) -*"If you got economies of scale technology to the point that the present costs reduced massively, great, but if you also remove the biggest revenue by the cobalt, then you don't have an awful lot of other revenue in order to offset these processing costs."* (Manager_Recycler_A)

Aggregate dimension	Second-order theme	First-order theme	Representative quotations
Sustainability strategies	Collaboration	New service development	*"we are having those kinds of discussions … I think it's beneficial because it is too much for one company to do at the moment given the capabilities that different companies have. I think it makes sense to have people weapons together, yeah, so that you can offer a kind of a full service."* (Manager_Recycler_A)
	Partnership building	Partner selection	*"we would prefer to work with someone upstream, someone … that could do the sort of preliminary discharging and dismantling and then give us the modules."* (Manager_Recycler_A)

6.5. Case study 4 – Repurposer_A

6.5.1. Company background

Repurposer_A is a company that produces lithium batteries for energy storage applications that are designed following circular economy principles. The batteries of Repurposer_A have a modular design that makes them easy to repair, upgrade, and efficiently reuse and recycle. One of the main characteristics of the design of Repurposer_A batteries is that they have completely removed the use of bonded or fixed components commonly used in most lithium-ion batteries. Repurposer_A and its team are responsible for designing, manufacturing, project delivery and servicing the batteries produced. Repurposer_A has developed batteries that can be used for several applications, such as powering motorhomes, all-terrain vehicles (ATV), scooters and remote telecoms stations. The company has also developed a solar energy storage system that can be used for residences and other commercial applications

The company is currently working on a project (ProjectRep_A) to create a small mobile facility to produce batteries using waste cells. The mobile facility has all the necessary stations, tools, equipment and resources for assembling, servicing and repurposing waste cells. The first repurposing battery pilot is taking place in Africa and will be used to provide energy to a refugee camp. In the first stage of the project, the mobile facility is planned to be used in remote regions. According to Director_Repurp_A a large stream of these waste cells could come from EoL EV batteries, therefore in the future, Repurposer_A plans to expand the scale of ProjectRep_A and design and work with its strategic partners to implement larger repurposing facilities.

6.5.2. Drivers and barriers for implementation of environmental strategies

Drivers

From the point of view of Head_Grants_Repurp_A, the most important driver for entering the repurposing EV battery business is related to the value of the EV batteries and it components at the end of their automotive life. Head_Grants_Repurp_A explained that when EV batteries reach their EoL for the automotive industry, they still have 80% of their capacity. According to Head_Grants_Repurp_A, *"there is so much value within them (EV batteries) that you could reuse. That is why taking them straight to recycle is just madness. There is a lot you can do before it gets to that point (recycling)."* Head_Grants_Repurp_A suggested that the technology in the Lithium-ion could be used for energy storage applications; however, these batteries are more expensive than lead-acid batteries. Head_Grants_Repurp_A argued that the EoL routes for lithium-ion batteries are not clearly defined and that recycling lithium-ion batteries is an energy-intensive process. Director_Repurp_A reinforced the idea that recycling EoL lithium-ion batteries should not be the first option saying: *"recycling process is carbon-heavy, expensive, energy-intensive, and the proportion of material that can actually be recovered is relatively low".* Moreover, to produce a new battery with the recycled material, *"you still have to go and take that recovered material and take it all the way back to the first step and build a brand new battery. Which is still energy intensive, expensive and carbon-heavy"* (Director_Repurp_A)

As explained by Head_Grants_Repurp_A, another important driver for entering the EoL management market by offering battery repurposing solutions is the opportunity to improve the technology currently used in batteries for energy storage applications. The energy storage solutions mainly use lead-acid batteries, which are not efficient nor environmentally friendly. As he suggested, there is a need for upgraded batteries with eco-designs. Head_Grants_Repurp_A indicated that "*there is a consensus in the industry that the batteries are being used for energy storage (lead-acid batteries) are a weak point".* Head_Grants_Repurp_A suggested that lead-acid batteries tend to have faults and are affordable but not environmentally friendly. As Head_Grants_Repurp_A suggested, *"they are prompt to have faults and cannot be maintained... they are not meant to be maintained and not designed to get the maximum value which screams for somebody to think differently"* (Head_Grants_Repurp_A).

Director_Repurp_A suggested that one of the reasons that encouraged the company to design sustainable products and work on repurposing projects was the recent product design legislation. As stated in one of the interviews, *"EU Ecodesign legislation [7] helped to force the design of cleaner products and the right to repair. That legislation was useful for us" (Director_Repurp_A).* Moreover, Director_Repurp_A mentioned that the product design legislation is promoting to keep products and components in circulation for a more extended period of time, and that is what the company is trying to achieve with their products and projects, even though the battery industry is not following that path yet.

Barriers

Head_Grants_Repurp_A and Director_Repurp_A agreed that the batteries EoL management legislations are the main barrier for companies interested in entering the market of second-life applications of EV batteries. Head_Grants_Repurp_A suggested that since there have been problems with lithium-ion batteries in the past and lithium-ion batteries are categorised as dangerous goods [8], the legislations restrict the use of second-life cells and their transportation. According to Head_Grants_Repurp_A, *"rules are not clearly defined for (EV batteries) second life used, and the rules are lagging behind the technological advances[9]".* As Director_Repurp_A argued, several academic authors that talk about circular economy [10] recommend prioritising reuse, then reuse and finally recycle. However, as he suggested, *"when it comes to battery legislations, they jump straight from use to recycle, and there is no reuse in the middle"* (Director_Repurp_A). According to Director_Repurp_A, battery legislations state the take-back obligations for automotive batteries at their EoL, the responsible parties and recycling targets. Director_Repurp_A explained that legislation is not contemplating the reuse of EV lithium batteries and components which could be significantly beneficial due to the high value of the battery components. As mentioned by Director_Repurp_A, "*the*

---

[7] Ecodesign for sustainable products: European Commission is proposing a regulation for setting ecodesign requirements for sustainable products. The regulation rules will apply to all products on the internal market to make them more durable, reusable, reparable, upgradable, recyclable, and more environmentally friendly (European Parliament, 2022).

[8] Lithium ion batteries are made of hazardous materials (e.g. lithium metal, flammable solvents) that can cause an exothermic reaction within the battery and cause fires as it has happened in several occasions (Lisbona and Snee, 2011).

[9] Some EV battery cell manufacturers such as BYD, GM and CATL are developing new batteries that are less prone to catch fire (Reuters, 2021).

[10] Circular economy is and economic system that replace the EoL concept with reducing, reusing, recycling and recovering materials in production/distribution and consumption processes. (Kirchherr, Reike and Hekkert, 2017; Potting *et al.*, 2017) .

current legislation is driving EV batteries towards recycling without taking into account the options in the middle, which is actually what else could you do with it".

The representative quotations for the drivers and barriers are summarised in Table 6.13. The quotations are organised by the aggregate dimension, first-order themes and second-order themes. The categories for the aggregate dimensions and second-order themes are "a priori" extracted from previous literature (Govindan and Bouzon, 2018; Govindan and Hasanagic, 2018; Narimissa, Kangarani-Farahani and Molla-Alizadeh-Zavardehi, 2020) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** While the first-order themes were derived from the findings.

Table 6.13. Drivers and barriers for the implementation of environmental strategies in the EoL EV battery industry Repurposer_A (Author, 2024)

Aggregate dimension	Second-order theme	First-order theme	Representative quotations
Drivers for the implementation of sustainability strategies	Economic	Value recovery	-*"The biggest reason to go for reuse in lithium-ion batteries is that they reach their end of life when they still have 80 % of their capacity. So there is so much value within them that you could reuse."* (Head_Grants_Repurp_A) - *"recycling process (of lithium-ion batteries) is carbon-heavy, expensive, energy-intensive and the proportion of material that can actually be recovered is relatively low"*(Director_Repurp_A)
Drivers for the implementation of sustainability strategies	Technology and infrastructure	Eco-design	-*"Lead-acid batteries ... are very cheap, but they are not very environmentally friendly...they are prone to having faults".* (Head_Grants_Repurp_A) -*"the products (lead-acid batteries) are not sustainable. They are not meant to be maintained and not designed to get the maximum value which screams for somebody to think differently".* (Head_Grants_Repurp_A)
Drivers for the implementation of sustainability strategies	Policy	Product Design legislation	-*"EU legislation helped force that adoption to design cleaner products and the right to repair . That legislation was useful for us."* (Director_Repurp_A) - *"In the legislation is there, and they are trying to drive better behaviour and try to encourage keeping products in circulation longer"* (Director_Repurp_A)

Aggregate dimension	Second-order theme	First-order theme	Representative quotations
Barriers for the implementation of sustainability strategies	Policy	EoL management legislation	*-"Legislations are more a barrier for companies that are interested in getting involved in the second life applications of EV batteries".* (Head_Grants_Repurp_A). *'-"Many authors' common phrases are: reduce, reuse and recycle. When it comes to battery legislations, they jump straight from use to recycle, and there is no reuse in the middle".* (Director_Repurp_A)

6.5.3. EoL Reverse supply chain elements

Processes

The analysis of the processes followed by Repurposer_A at ProjectRep_A to repurpose EV batteries is provided below.

Repurposer_A receives waste cells from its suppliers. When the waste cells arrive at Repurposer_A facilities, one of the first steps is to do an initial visual quality assessment and preparation to move on to the next step. Once all 160 cells have passed the visual inspection and preparation, these are labelled and loaded into a cell tester with 160 channels. Then, the good cells that passed that test are stored, and the bad ones are taken from the cell tester and put in a disposal bin. Once they have 128 appropriate good cells, the operational staff can assemble a Portable_RepurposedBattery. After a battery is assembled, the new battery pack needs to pass a pack testing exercise. The batteries that pass the test are stored and ready to be delivered to clients. In contrast, the batteries that do not pass the test have to pass through a rework process.

According to Head_Grants_Repurp_A, the battery assembly process has been designed to be safe and simple. As he suggested, *"there is no welding, there is no glue, there are no toxic chemicals".* As he continued explaining, *"it is just putting the cells in the right order, doing some checks to verify that the pack has been assembled in the right way and then they just put it all together and test".* Head_Grants_Repurp_A argued that the way the repurposing process was designed has significant implications for the labour requirements of the operational staff. As he suggested, *"for the future, the training skills and knowledge is significantly reduced when compared to building a traditional battery".*

One of the main limitations of the ProjectRep_A repurposing process is the low tolerance of the cell testing machine. As Director_Repurp_A suggested, *"the tolerance on the (cell) pass rate is actually quite low… the limitation (of the repurposing process) is not the time* *available to build the packs, but is probably more the testing".* Director_Repurp_A explained that the machine used for cell testing at ProjectRep_A has only 160 channels (160 cell spaces), and they need 128 cells to be able to produce one repurposed battery. As he suggested, "*If we have a good ratio of 25%, then we would need to do 4 rounds of the cell tester to get one battery pack out".* Considering that each round of cell testing takes about 4 hours (fixed time) with a ratio of 25% of goods cells per round, testing cells to build one battery could take up to 16 hours. Director_Repurp_A argued that *"ideally out of the 160 channels that we got available (in the cell tester), I want at least every single time 128 good sales coming off so I can continue to build 1 pack per cycle. Anything less than that makes us lose productivity."*

The representative quotations for the processes characteristics are summarised in Table 6.14. The quotations are organised by the aggregate dimension, first-order themes and second-order themes. The categories for the aggregate dimensions and second-order themes are "a priori" extracted from previous literature (Fleischmann, Ronald and Dekker, 2000) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** In contrast, the first-order themes were derived from the findings.

Table 6.14. Characteristics of the process in the EoL EV battery industry

Aggregate dimension	Second-order theme	First-order theme	Representative quotations
Process	Assembly	Safety	*"There is no welding, there is no glue, there are no toxic chemicals".*(Head_Grants_Repurp_A)
	Assembly/Testing (Battery)	Simplified procedure	- *"It is just putting the cells in the right order, do some checks to verify that the pack has been assembled in the right way, and then they just put all together and test"*(Head_Grants_Repurp_A) -*"for the future, the training skills and knowledge it is significantly reduced when compared to building a traditional battery"* (Head_Grants_Repurp_A)
	Testing (cells)	Low tolerance	-*"the tolerance on the (cell) pass rate is actually quite low..the limitation is not the time available to build the packs, but is probably more the testing".* (Director_Repurp_A) -*"I want at least every single time 128 good cells coming off...anything less than that make us loose productivity."* (Director_Repurp_A)

Relationships

The analysis of the interviews and secondary data suggests that the development of the repurposing containerised facility of ProjectRep_A demanded the participation of different strategic partners.

One of the strategic partners that participated in ProjectRep_A was Eng&Man_A, a company that specialises in engineering and manufacturing. Eng&Man_A supported Repurposer_A to develop the battery manufacturing process and cells repurposing process for the ProjectRep_A facility. Another strategic partner involved in the development of the ProjectRep_A facility was University_A. Univeristy_A and, in particular, the team of the Electrochemical laboratory supported Repurposer_A with their lab-based expertise to develop circular economy processes for ProjectRep_A. According to Director_Repurp_A, after the completion of ProjectRep_A, Repurposer_A will continue its partnership in the form of a Knowledge Transfer Partnership (KTP)[11] with University_A to improve their cell testing techniques. As Director_Repurp_A suggested, *"we've got some partners on that are looking at acoustic assessments of cells …and also visual testing analytics".*

Another important group of partners of Repurposer_A are international organisations such as DevelopBank_A and ItlOrgMigration_A. As Director_Repurp_A suggested most of the work that Repurposer_A has done in Africa and the Caribbean is based on grants. Director_Repurp_A indicated that *"we are working with a lot of international organisations to support them with looking for (energy) solutions".* According to Director_Repurp_A, the grants received from international organisations are used to fund Repurposer_A projects that provide technical knowledge to the people who live in the area and offer product solutions to the region. As explained by Director_Repurp_A, the relationships with international organisations and the work that they have conducted together have given Repurposer_A several benefits. One international organisation that has worked with Repurposer_A and has become a strategic partner is the DevelopBank_A. DevelopBank_A is an institution that finances sustainability projects in Latin America and the Caribbean. DevelopBank_A is sponsoring a Repurposer_A project that consists of an energy storage solution for hotels in the Caribbean. As Director_Repurp_A indicated, "*they (DevelopBank_A) are giving us the grant money to*

[11] Knowledge Transfer Partnerships is a partly government-funded programme to encourage collaboration between businesses and universities (academics and graduates) in the United Kingdom (KTN, 2023)

develop all of the necessary core systems that we need to be able to scale second-life applications (of waste cells) into these credible markets". On the other hand, ProjectRep_A was also partially funded by ItlOrgMigration_A. As Director_Repurp_A indicated, ItlOrgMigration_A also provided Repurposer_A with access to trial their pilot ProjectRep_A facility in a refugee camp run by them (ItlOrgMigration_A).

With regards to the relationship and projects with international organisations, Director_Repurp_A stated, "*We've seen some good success here…we've shared that risk of embarking upon this journey together... we can see a route to commercial operation (for Repurposer_A batteries' solutions)".* Director_Repurp_A argued that the relationship with international organisations and the pilots conducted with them are vital to prove that Repurposer_A battery solutions have worked in field applications and not only had an environmental influence in the ecosystem but also economic and social implications to justify a commercial operation. As Director_Repurp_A explained, *"if you can say (to potential customers) we did a trial of a mobile mini-grid of our batteries… which leads to this much impact on the economy or this much improvement in life…. it's easy to justify that there is a market there."*

The representative quotations for the relationships are summarised in Table 6.15. The quotations are organised by the aggregate dimension, first-order themes and second-order themes. The categories for the aggregate dimensions and second-order themes are “a priori” extracted from previous literature (Lambert, Emmelhainz and Gardner, 1996) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** In contrast, the first-order themes were derived from the findings.

Table 6.15. Relationships between focal company and other EV battery supply chain actors (Author, 2024)

Aggregate dimension	Second-order theme	First-order theme	Representative quotations
Relationship	Type I partnership	Universities	*"we've got some partners on that are looking at acoustic assessments of cells that involves ultrasound, rapid testing methodologies, electromagnetic spectrum …and also visual testing analytics"* (Director_Repurp_A)
	Type I partnership	International Organisations	-*" a lot of the work we're doing is all to do with grant based activity... they're giving us the grant money to develop (our projects)"* -*"we are working with a lot of international organisations to support them while looking for (energy) solutions".* - *"We've seen some good success here…we've shared that risk of embarking upon this journey together... we can see a route to commercial operation (for Repurposer_A batteries' solutions)"* (Director_Repurp_A)

6.5.4. Sustainable EoL Reverse supply chain

Sustainable supply chain strategies

According to the interview analysis, some of the sustainability strategies identified are related to the collaboration of Repurposer_A and University_A to improve the repurposing process efficiency.

Repurposer_A has started working on a new project similar to ProjectRep_A, but at a larger scale, called ProjectRep_B. As was identified in the analysis of the ProjectRep_A repurposing process, cell testing was the bottleneck of the process. For ProjectRep_B, Repurposer_A is planning to improve the efficiency of the repurposing process by looking for new techniques to improve the testing process. In order to achieve that goal, Repurposer_A is collaborating with University_A. Repurposer_A sought the support of University_A to implement new rapid cell testing methodologies such as acoustic assessment involving ultrasound that, in two or three minutes, can estimate the expected cell quality. As Director_Repurp_A suggested, "*we are trying to combat that using a new set of techniques from University_A for acoustic testing."* The acoustic assessment will help Repurposer_A increase the quality of the cells entering the cell testing machine. Director_Repurp_A argued, *"if the quality of the cells on the impound is good anyway, we may only be talking about making sure that the difference is between 85% to 95%".*

University_A is also supporting Repurposer_A to develop visual analytics techniques for the pack assembly process. Visual analytics is planned to be introduced in the battery assembly process of ProjectRep_B to help operators to put the cells inside the battery pack in the right position. Director_Repurp_A suggested that visual analytics will help to *"indicate whether the operator has put the cells in the right position in the right orientation".* Director_Repurp_A argued that the implementation of visual analytics could increase to up to 99.5% the percentage of batteries that pass the battery pack test. According to Director_Repurp_A, the implementation of visual analytics will ensure that *"a very high percentage of certainty that the pack has been built correctly, which should then go through to the pack tester with a high degree of certainty (99%-99.5%) that it will pass."*

Director_Repurp_A suggested that in their current ongoing pilots, between 90% to 95% of the batteries pass the battery pack test. Whereas in the case of new teams, that percentage could go down to 70%. As Director_Repurp_A explained, it is not only inefficient to have such rates but also dangerous for the operators. As he suggested, *"We have to be really careful because at that point (70%) you are in the fire territory because you're charging something that's gonna short circuit and potentially go into thermal runway".* For that reason, Director_Repurp_A argued, *"we are applying quite a lot of technology into the error-proofing side of the build."*

The analysis of the interviews suggests that the collaborative development of acoustic testing and visual analytics will have economic and environmental implications for Repurposer_A. As Director_Repurp_A suggested, if most of the cells that enter the cell testing machine and the battery packs are correctly assembled in the first attempt, *"we're not wasting labour, energy and time, and then that boosts the throughput".* But also, the error-proving techniques will have social implications by increasing the safety of operators.

Another important sustainability strategy that Repurposer_A is working towards is related to the company's future business model. Director_Repurp_A argued that Repurposer_A aims to approach EV manufacturers to offer them a repurposing solution for their EoL EV packs. Director_Repurp_A said they want to demonstrate that new batteries for second applications can be built from EV batteries, which represents a cheaper solution for their waste management needs. However, Repurposer_A future business model does not consist of offering repurposing services, nor building repurposing facilities or assembling second-life batteries, instead, they are aiming to have their technology licensed to facilitate their clients to repurpose their batteries. As Director_Repurp_A explained, "*we build batteries right now, but actually, that's not the end goal here... we want to facilitate other people building batteries … companies might be able to lease or rent from us… we're not interested in dominating everybody's market capability. We want the technology to be licenced".*

As Director_Repurp_A argued, the Repurposer_A business model aims to help companies *"overcome some of the capital blockers"*. Director_Repurp_A said that they want to tell their potential clients, *"I'm going to charge you £X a month to have this facility which gives you the data, the knowledge, the information, the tools.. to create batteries from second life cells".* That way, as Director_Repurp_A said, *"companies will not need masses of capital investment CapEx.. they will be doing an OpEx exercise".* Director_Repurp_A added that the repurposed batteries would come with a digital Battery Passport that will keep the records of all battery parts and cells, and every time the battery is serviced and the cells are replaced, that Battery passport gets updated. Director_Repurp_A argued that they are planning to add traceability to their products so companies can prove the life extension of the cells after their first life applications. As Director_Repurp_A stated, "*we're hoping to introduce the levels of traceability within our products so that you as a consumer …. know that the cells that came from your battery have now gone over to a different county and are powering a light to a community".* The information from the Battery passport will prove that, as Director_Repurp_A said, "*we've diverted them (the cells) away from landfill. And that they (the cells) have gone into another application… you would then be able to trace individual cells and know through how many different applications it was in."*

From the analysis of the interview, the new business model strategy proposed by Repurposer_A could have significant economic, environmental and social implications. The strategy of licensing the technology and facilitating companies repurposing solutions will help Repurposer_A to make their business offer economically viable. Moreover, the companies interested in repurposing using Repurposing_A technology to overcome the capital investment barriers. Extending the life of cells in second-life applications already has a positive environmental impact. However, the possibility of proving where the cells have been used throughout her extended lifetime is valuable information for companies aiming to prove their green credentials. The traceability of Repurposer_A batteries could also be used to prove the social impact of the batteries in the communities where the batteries are produced and used.

The representative quotations for the sustainability strategies are summarised in Table 6.16. The quotations are organised by the aggregate dimension, first-order themes and second-order themes. The categories for the aggregate dimensions and second-order themes are “a priori” extracted from previous literature (Beske, Land and Seuring, 2014) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** In contrast, the first-order themes were derived from the findings.

Table 6.16. Future sustainability strategies (Author, 2024)

Aggregate dimension	Second-order theme	First-order theme	Representative quotations
Sustainability strategies Sustainability strategies	Collaboration	Joint Development	-*"the time sink in the cell tester that we need to overcome..we're trying to combat that using a new set of techniques from University_A for acoustic testing."*(Director_Repurp_A) -*"There is some visual analytics also will be introduced thanks to University_A…that visual analytics piece is really there to reduce the amount of rework."* (Director_Repurp_A) -*" we want everything going for testing to be good because then we're not wasting labour, energy and time, and then that boosts the throughput"*.(Director_Repurp_A)
	Innovation	Business model	*"we build batteries right now, but actually, that's not the end goal here... we want to facilitate other people building batteries .. We want the technology (the knowledge, the information, the tools) to be licenced"* *"our batteries will come with a battery passport..that keeps a record of all of the parts and all of the cells... and gets updated every time that battery is serviced."* -*"we're hoping to introduce the levels of traceability within our products so that you as a consumer …. know we've diverted them (the cells) away from landfill."*

6.5. Case study 5 – OEM_A

6.6.1. Company Background

OEM_A is a manufacturer of automobiles, motorcycles and power equipment with a presence in America, Europe and Asia. OEM_A produces cars with different powertrain technologies, such as electric vehicles, hybrid vehicles (HV), fuel cell vehicles, plug-in hybrid vehicles, and gasoline engine vehicles. OEM_A has a partnership with RecyclerEurope_A, which is currently in charge of the collection of EV batteries for recycling. Manager_OEM_A explained that the recycling process for EV lithium-ion batteries is currently in an early phase. RecyclerEurope_A has established only a pilot scale hydrometallurgy to recycle EV batteries because there are not many returning batteries yet.

6.6.2. Drivers and barriers to implementation of environmental strategies

Drivers

Manager_OEM_A shared his thoughts about the main drivers that led them to establish OEM_A current EoL management strategy for EV batteries. OEM_A made a partnership with the company RecyclerEurope_A to collect and recycle the batteries that their life has ended? eir EoL since OEM_A still has low volumes of returning batteries. As mentioned by Manager_OEM_A, *"I think that it's all too early for them (batteries) to start coming back to our dealer network".* Manager_OEM_A argued that OEM_A competitors are expanding the warranty period of EV batteries from eight to ten years and even to twelve years in some cases. Hence, the EV batteries will stay in the vehicles for at least ten years unless, as Manager_OEM_A suggested, the cars have an accident, and the battery gets damaged and reach its EoL. According to Manager_OEM_A, OEM_A is a small player in the European market. The company has only started to introduce large volumes of lithium-ion batteries in the market since the release of Car_A[12]. From the lithium-ion batteries introduced in the market, they have only received three malfunctioning batteries and nineteen from crashed cars that were used at the European New Car Assessment Program (Euro NCAP)[13].

According to Manager_OEM_A, car manufacturers' EoL management decisions will be driven by the new battery regulations. Manager_OEM_A indicated that the European Commission is currently working on a revision of the battery regulations[14]. He added that the waste framework section, in particular the transport regulations and the time when the battery becomes waste, is being revised by the European Commission in the stakeholder consultation. As mentioned by Manager_OEM_A, *"battery regulations are defining what we as car manufacturers have to do with our batteries at their EoL."* Manager_OEM_A mentioned that by 2023 the new battery regulations were expected to be published and the members of the European Union have eighteen months after the regulation publication to adopt the new rules into their national legislations. As explained by Manager_OEM_A, between 2024 and 2027, there will be a transition period, but as he highlighted, *"from 2027 everything needs to be in place…within that time span (2024-2027), the development of that whole (EoL) market has to occur."*

Barriers

[12] The first generation of hybrid vehicles of CarModel_A was released in 2017
[13] Euro NCAP has created the five-star safety rating system to help consumers, their families and businesses compare vehicles more easily and to help them identify the safest choice for their needs (Euro NCAP, 2023)
[14] The new Regulation will replace the existing Batteries Directive from 2006. This new cradle-to-grave regulatory framework for batteries will require a lot of more detailed rules (secondary legislation) to be adopted from 2024 to 2028 to be fully operational. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7588

Manager_OEM_A mentioned that OEM_A is looking for opportunities to close the loop of their operations by retrieving the materials recycled from their batteries. The company's recycling partner, RecyclerEurope_A, through its hydrometallurgy recycling process, can recover the materials of recycled batteries e.g. lithium, copper, nickel and cobalt. As Manager_OEM_A argued, "*We (OEM_A) are looking into the opportunity of buying back those materials"* that, according to the legislation, will become mandatory. However, Manager_OEM_A argued that setting targets of recycled materials for the production of new batteries represents a hurdle for OEM_A and the rest of the car manufacturers. As Manager_OEM_A suggested, *"According to the regulations, we need to have a certain percentage of our materials used back into new batteries*[15]*. The only problem and discussion that we are having is the composition, because the material composition of our batteries is constantly evolving".* Manager_OEM_A explained that EV batteries will probably be used in the cars for approximately ten years. Then they will be used for 20 years or even longer in their second life (stationary energy storage applications). Manager_OEM_A suggested that "*by the time your battery actually returns for material recycling, whatever you put on the market now will come back somewhere 2045, 2050… By that time the type of battery that we will have it's not going to be a lithium-ion battery, it is probably going to be something different".*

Manager_OEM_A also mentioned that they were assessing the opportunity to refurbish OEM_A batteries. However, they have encountered some additional barriers in the legislation. As Manager_OEM_A explained, to refurbish EV batteries, it is necessary to have modules and cells in good condition available for replacing the damaged modules and cells. Manager_OEM_A mentioned that "*in the legislation, there is a clause included that if your battery … goes from a battery pack to module or to cell level… if you want to put those modules onto the market as an individual component, you need to have special type approval for that one component."* Manager_OEM_A added that OEM_A is looking at how to ask for that component approval. However, as he argued, at the moment, OEM_A does not have modules in the market yet.

According to Manager_OEM_A, one of the barriers that OEM_A faces to handle batteries at their EoL is related to the availability of skilled technical labour. Manager_OEM_A suggested that they are still evaluating if they want to do the collection in-house because of the training requirements. As explained by Manager_OEM_A, *"We cannot have all our dealers certified to handle high voltage cars. You need a quite extensive training…which*

[15] The new battery regulation will ensure that valuable materials are recovered at the end of their useful life and brought back in the economy by adopting stricter targets for recycling efficiency and material recovery over time. Material recovery targets for lithium will be 50% by 2027 and 80% by 2031. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7588

is a legal requirement in order to handle high voltage products." OEM_A has approximately 5,000 registered dealers in Europe. Manager_OEM_A indicated that they could not train the staff of all the dealer service centres to receive and process EV batteries. As Manager_OEM_A suggested, the company is currently in the process of selecting dedicated dealers to receive EoL EV batteries. Manager_OEM_A explained, *"We need to identify like big dealerships in dedicated markets. So the most important markets for OEM_A would be UK, France, Italy, Spain, Germany."*

OEM_A has been encountering another significant barrier to shipping battery waste to mainland Europe since Brexit. Manager_OEM_A explained that when lithium-ion batteries are transported, they must follow the relevant legislation depending on the mode of transport used. As Manager_OEM_A mentioned, two legislations are applicable to the transport of batteries, road transport legislation[16]and sea transport[17]. In addition, Manager_OEM_A highlighted that "*once you consider a battery for the purpose to be sent for recycling, then you are not talking about dangerous goods, but dangerous waste. And if you want to ship dangerous waste, there is a whole bunch of requirements that you need to comply…It's not so easy to have that done."*

Manager_OEM_A mentioned that there is an environmental convention called the "Basel Convention" [18] which applies to the shipping of hazardous waste cross-border. According to the convention, people cannot ship hazardous waste across borders to another country, not even within the EU. He said that within the EU, it is mandatory to send a notification called Prior Informed Consent (PIC)[19] to request approval to send hazardous waste from one country to another. The approval process takes approximately five months. However, Manager_OEM_A explained that the EU member states have an agreement between them. *"Instead of having that notification process, there is a shortcut which is determined in a document called M259 and this is a mutual agreement between two member states…If I have a battery in Sweden, I can ship it to France provided that the Swedish authority and the French Authority agree Swedish authority to ship and French authority to accept."* (Manager_OEM_A). However, as Manager_OEM_A suggested, *"The problem is the UK has left the EU and that agreement is no longer existing… you simply cannot ship batteries from the UK to mainland Europe anymore."*

[16] Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR)
[17] International Maritime Dangerous Goods Code (IMDG Code)
[18] The overarching objective of the Basel Convention is to protect human health and the environment against the adverse effects of hazardous wastes. Its scope of application covers a wide range of wastes defined as "hazardous wastes" based on their origin and/or composition and their characteristics, as well as two types of wastes defined as "other wastes" - household waste and incinerator ash.
[19] Prior Informed Consent (PIC) procedure

The representative quotations for the drivers and barriers are summarised in Table 6.17. The quotations are organised by the aggregate dimension, first-order themes, and second-order themes. The categories for the aggregate dimensions and second-order themes are "a priori" extracted from previous literature (Govindan and Bouzon, 2018; Govindan and Hasanagic, 2018; Narimissa, Kangarani-Farahani and Molla-Alizadeh-Zavardehi, 2020) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** While the first-order themes were derived from the findings.

Table 6.17. Future sustainability strategies (Author, 2024)

Aggregate dimension	Second-order theme	First-order theme	Representative quotations
Drivers for the implementation of sustainability strategies	Market and competition	Industry evolution	*"I think that it's all too early for them (batteries) to start coming back to our dealer network".* (Manager_OEM_A)
	Policy	Battery regulations	*-"battery regulations are defining what we as car manufacturers have to do with our batteries at their EoL"* *- "the new battery regulation is expected to be published in 2023… But as from 2027 everything needs to be in place...within that time span, the development of that whole market has to occur.* (Manager_OEM_A)
Barriers for the implementation of sustainability strategies	Policy	Battery regulations	*if you look into the new battery regulation, ... we need to have a certain percentage of our materials used back into new batteries. The only problem is the composition... the material composition of our batteries is constantly evolving.* (Manager_OEM_A)
	Policy	Battery regulations	*"Now in the legislation, there is a clause included that if your battery … goes from a battery pack to module or to cell level, if you want to put those modules onto the market as an individual component, you need to have special type approval for that one component."* (Manager_OEM_A)
	Technology and infrastructure	Skilled technical labour	*- "We cannot have all our dealers certified to handle high voltage cars. You need a quite extensive training…which is a legal requirement in order to handle high voltage products."* *- "We cannot do this for each and every dealer, so we need to make a selection of dedicated dealers for this... this is an ongoing process within the OEM_A organisation in Europe, we don't have that established yet".* (Manager_OEM_A)

Aggregate dimension	Second-order theme	First-order theme	Representative quotations
Barriers for the implementation of sustainability strategies	Policy	Dangerous waste transport legislation	*-"You cannot simply ship hazardous waste just across border to another country, even within the EU. Member States within the EU have made an agreement … instead of having that notification process (PIC), there is a shortcut ....* *- "The problem is the UK has left the EU and that agreement is no longer existing… you simply cannot ship batteries from the UK to mainland Europe anymore"* (Manager_OEM_A)

6.6.3. EoL Reverse supply chain elements

Process

The processes agreed upon between Manager_OEM_A and RecyclerEurope_A for the recovery of EV batteries from the market are described below.

RecyclerEurope_A has a transport service provider in each European country. As explained by Manager_OEM_A, "*RecyclerEurope_A has established an IT system where any dealer and ATF can go online and register to be able to have their business to get their batteries collected*." The person responsible at the Dealer and ATF has to register detailed information about their business such as address, VAT number[20] , and pick up location. Once registered, they can request their batteries to be collected by providing some additional information (e.g. quantity, type battery and size) about the battery or batteries to be collected. This information is automatically completed for OEM_A vehicles by inserting the model of the vehicle and the year. In the collection request, ATFs and Dealers must complete a checklist with questions related to the state of the battery, e.g. damaged, not damaged, etc. RecyclerEurope_A will contact the dealer or ATF if necessary to gather additional information about the state of the battery. If the battery is damaged, RecyclerEurope_A will send special safe packaging following the road transport regulations to avoid the battery catching fire. RecyclerEurope_A has

[20] VAT registration number, this is the unique number that identifies a taxable person (business) or non-taxable legal entity that is registered for VAT.

a contractual agreement with OEM_A to pick up the batteries within fourteen days of the request.

After the business registers the collection request, RecyclerEurope_A arranges with a local logistics service provider (LSP), which may vary depending on the country. In the case of the UK, "*They are collecting the batteries but they store the batteries in one of their warehouses in safe locations"* (Manager_OEM_A). The UK LSP would momentarily store the batteries because they cannot just ship one battery to RecyclerEurope_A in France. The UK LSP need to maximise the load of the lorries to ship a full load to France. Due to the transport restriction between the UK and mainland Europe because of Brexit, according to Manager_OEM_A, "*what is currently happening in the UK is all those batteries are stockpiling in warehouses somewhere and there is no treatment facility in the UK".* He explained, *"this is an issue for the whole industry and it's not even the car industry because it's also valid for the small pocket batteries"* (Manager_OEM_A).

The representative quotations for the process characteristics are summarised in Table 6.18. The quotations are organised by the aggregate dimension, first-order themes and second-order themes. The categories for the aggregate dimensions and second-order themes are "a priori" extracted from previous literature (Fleischmann, Ronald and Dekker, 2000) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** In contrast, the first-order themes were derived from the findings.

Table 6.18. Characteristics of the process in the EoL EV battery industry (Author, 2024)

Aggregate dimension	Second-order theme	First-order theme	Representative quotations
Process	Collection	Decentralised outsourced transport	-*"RecyclerEurope_A has in each and every country logistics service providers (LSP). So basically these LSP collect the batteries upon the request of RecyclerEurope_A"* (Manager_OEM_A)
		Standardised registration system	-*" RecyclerEurope_A has established an IT system where any dealer and ATF can go online and register to be able to have their business to get their batteries collected"* (Manager_OEM_A)
		Stockpiling	- *"What is currently happening in the UK is all those batteries are stockpiling in warehouses somewhere and there is no treatment facility in the UK"* (Manager_OEM_A)

Relationships

OEM_A has a contractual partnership with RecyclerEurope_A to collect, recycle and dispose of EoL batteries from hybrid and electric vehicles in 22 countries in Europe, including the UK. RecyclerEurope_A has a pilot plant that uses hydrometallurgical techniques to extract raw materials such as cobalt, lithium, copper, and plastic from old batteries. As Manager_OEM_A indicated, "*We (OEM_A) have a contract… that transfer of what is called extended producer responsibility (EPR)".* Manager_OEM_A explained that the transfer of the EPR happens when a Dealer or ATF place a collection request. He explained that from a contractual point of view, OEM_A is not responsible for what happens to the battery since a collection is requested. However, as Manager_OEM_A indicated, *"We as OEM_A don't want to be in the newspaper tomorrow with a headline saying that a truck got burnt with a OEM_A battery which was not properly packaged. So we are trying to have some kind of control on what is going on."*

As stated in the interview with Manager_OEM_A, OEM_A is assessing the option to build second-life batteries through RecyclerEurope_A, in-house and with other partners. They are assessing the best option in the long term, which will involve changing the partnership agreements with RecyclerEurope_A or building a partnership with other companies to transfer the liability of the second-life batteries. As stated in the interview, "*there's as well a problem there (using batteries for second-life applications) because of the liability who is going to be responsible of the management of that battery if you use that battery for a different industry or different purpose."* (Manager_OEM_A)

The representative quotations for the relationships are summarised in Table 6.19. The quotations are organised by the aggregate dimension, first-order themes and second-order themes. The categories for the aggregate dimensions and second-order themes are "a priori" extracted from previous literature (Lambert, Emmelhainz and Gardner, 1996) and explained and justified in Chapter 4. Conceptual Framework and Chapter 5. Research Design. In contrast, the first-order themes were derived from the findings.

Table 6.19. Relationships between focal company and other EV battery supply chain actors (Author, 2024)

Aggregate dimension	Second-order theme	First-order theme	Representative quotations
Relationship	Partnership type II	Partnership with Recycler	*- We have signed a contract with RecyclerEurope_A…We have a contract… that transfer of what is called extended producer responsibility"*
	Absence of relationship - Future Partnership Type II	Partnership with companies for second-life application	*-"there's as well a problem there (using batteries for second-life applications) because of the liability who is going to be responsible of the management of that battery if you use that battery for a different industry or different purpose."*

6.6.4. Sustainability strategies

According to the interview analysis, some of the sustainability strategies identified are related to the collaboration of OEM_A, RecyclerEurope_A and other partners to give OEM_A batteries a second-life application or a full end-of-life management service.

OEM_A is assessing the option to build second-life batteries, and one of the options is to do it through collaboration with RecyclerEurope_A. OEM_A has sent a delegation of employees from R&D, sales and customer service to RecyclerEurope_A to identify what battery second-life services can be offered by RecyclerEurope_A. As explained in the interview, OEM_A needs to verify how RecyclerEurope_A is analysing the SOH of batteries to make the business profitable. As Manager_OEM_A explained, they need to know "*how they (RecyclerEurope_A) are analysing the batteries to guarantee that that second life business is profitable. Because if you do not make a proper analysis and you* *put bad cells into a second life application, you will have a problem*". According to Manager_OEM_A, they would like to identify if the battery analysis made by RecyclerEurope_A can also allow the battery repair and that the repaired batteries meet the OEM_A standards and quality level.

As Manager_OEM_A shared in the interview, OEM_A is doing its internal analysis of the potential of going into a second life business, but they have not decided yet if the best option is to do it in-house or through a partner. As indicated by Manager_OEM_A, "*the question is do we make this by ourselves? and if so, how do we put those products on the market? Or do we look for a joint venture partner? … do we join forces (with RecyclerEurope_A) because they already offer second-life applications to the market".* However, according to Manager_OEM_A, OEM_A does not discard the option to make a partnership with another company besides RecyclerEurope_A, as Manager_OEM_A explained, "t*owards the future, there will be much more players on the market, and it's my intention to go through a call for tender with various players in the European market to identify if RecyclerEurope_A is still the best partner for long-term".*

Manager_OEM_A mentioned that OEM_A is aiming to find a recycler and second-life partner that could offer them a full EoL service. As Manager_OEM_A suggested, *"We were looking for a partner that could offer a full (EoL) service that means since the collection (of the battery) the extended producer responsibility is transferred, organised transport, organised intermediate storage, report to the authorities how many batteries returned from the market."* According to Manager_OEM_A, there are other recyclers in the market specialised in hydrometallurgy, but they do not offer the collection service. Manager_OEM_A explained, *"we (OEM_A) have made an internal study on what is the internal cost for transport collection and debt holding, and we can never match a company like them (RecyclerEurope_A) because they not only make this job for OEM_A".*

The representative quotations for the sustainability strategies are summarised in Table 6.20. The quotations are organised by the aggregate dimension, first-order themes and second-order themes. The categories for the aggregate dimensions and second-order themes are "a priori" extracted from previous literature (Beske, Land and Seuring, 2014) and explained and justified in **Chapter 4. Conceptual Framework** and **Chapter 5. Research Design.** In contrast, the first-order themes were derived from the findings.

Table 6.20. Table 6.19. Future sustainability strategies (Author, 2024)

Aggregate dimension	**Second-order theme**	**First-order theme**	**Representative quotations**
Sustainability strategies	Collaboration	New Service Development	*"A OEM_A delegation going over to RecyclerEurope_A... to identify what is the service can be offered by RecyclerEurope_A in terms of second life"* (Manager_OEM_A) *- "the question is do we make this by ourselves? and if so, how do we put those products on the market? Or do we look for a joint venture partner?* (Manager_OEM_A) *- "Towards the future, there will be much more players on the market, and it's my intention to go through a call for tender"* (Manager_OEM_A)
		New Service Development	*"We were looking for a partner that could offer a full (EoL) service that means since the collection (of the battery) the extended producer responsibility is transferred, organised transport, organised intermediate storage, report to the authorities how many batteries returned from the market."* (Manager_OEM_A)

7. Findings and discussion from the cross-case study analysis

7.1. Introduction

This section presents the findings from the cross-case analysis of five companies with critical roles in the UK EoL RSC for EV batteries. Drawing on the initial conceptual framework, the goal of this chapter is to identify common patterns, differences, and new insights. This section starts by discussing the drivers' and barriers' influence on the development of EoL supply chains. Furthermore, the chapter explains the linkages between EoL processes, business relationships and the perceived influence on the sustainability of the UK end-of-life RSC supply chain.

7.2. Drivers and barriers for developing EV batteries EoL services

This section presents the perceived influence of the drivers and barriers to developing EV batteries EoL services on the RSC design elements and future supply chain strategies. First, the drivers are presented in section 7.2.1, and then the barriers are presented in section 7.2.2.

7.2.1. Drivers

The analysis of the interviews with managers and directors of the case study companies suggests that there are economic, policy, market and competition drivers that influence companies to develop EV batteries EoL services.

Market

The interviewees from companies OEM_A, Recycler_A and Repurposer_A suggest that the automotive market's evolution and changes are among the most critical drivers for developing EoL EV battery services. The interviewed companies noticed that during the last few years, the volume of EVs produced by automotive companies has been increasing at a fast pace (Remanufacturer_A, ScrapCarRecycler_A, Repurposer_A, OEM_A). For that reason, the companies involved in the ELV (End-of-life vehicles) management and battery industries have been studying and learning about the new characteristics of EV batteries as they expect that the electrification of the automotive industry will change how their businesses operate (Remanufacturer_A, ScrapCarRecycler_A).

Economic

Economic drivers were among the most important drivers identified in the interviews (Remanufacturer_A, Repurposer_A, Recycler_A). The economic drivers identified are related to business opportunities to develop EoL management services and the infancy of the EoL service providers in the UK. Remanufacturer_A, Repurposer_A, and Recycler_A have recognised that there is a business opportunity to offer services for EV batteries. The steady rise of EVs entering the market is expected to generate a high supply of EoL batteries in the next years, which is motivating companies to expand their portfolio of services and start developing lithium-ion EoL battery recovering services (OEM_A, ScrapCarRecycler_A, Remanufacturer_A). Moreover, the value of the battery components (e.g. modules, cells) and materials (e.g. cobalt, aluminium) after their first life in the automotive industry is another important economic driver (Remanufacturer_A, Repurposer_A, Recycler_A).

Policy

The batteries and waste batteries regulations prohibit the disposal and incineration of all types of batteries, including lithium-ion batteries, limit manufacturers' responsibilities and set recycling targets (European Commission, 2020a). As mentioned by EP_manager from OEM_A, *"battery regulations are defining what we as car manufacturers have to do with our batteries at their EoL."* According to Manager_OEM_A, the new battery regulation is expected to be published in 2023. After the updated battery regulation publication, there will be a transition period for the EoL RSC actors to adapt. According to the case study participants, the legislation related to ELV and batteries has passed through several changes and revisions during the last few years, and they are expected to continue adapting due to the constant changes in the industry.

Knowledge

Another important driver identified in the case studies is related to the existing knowledge of the companies about the automotive industry (OEM_A, ScrapCarRecycler_A, Remanufacturer_A, Repurposer_A) and recovery expertise (Remanufacturer_A, Recycler_A). ScrapCarRecycler_A and Remanufacturer_A, for instance, have experience providing services to companies in the automotive industry and have developed capabilities to service ICE vehicles. As Director_Reman_A stated, *"there was an opportunity for the business to make use of our experience offering remanufacturing services… but this time for electric vehicle batteries*." Companies such as Recycler_A have not provided services previously to car manufacturers; however, they have technical metal recovery capabilities. Similarly, Manager_Recycler_A argued that Recycler_A decided to use the company's experience and knowledge acquired from recovering metals from waste to develop a process for recycling lithium-ion batteries.

7.2.2. Barriers

The interviewees of companies OEM_A, Remanufacturer_A, Repurposer_A agreed that policies, technology and infrastructure are the main barriers for companies interested in remanufacturing, recycling and entering the market of second-life applications of EV batteries.

Policy

The analysis of the case studies suggests that battery regulations are one of the most crucial policy barriers to developing EoL EV battery services. The interviewees from companies such as OEM_A, Remanufacturer_A, and Repurposer_A agree that battery regulations limit the recovery work of batteries (e.g., remanufacturing and repurposing). According to the interviewees, battery regulations do not influence battery design transparency, which is vital for efficient and non-destructive disassembly (Remanufacturer_A, Repurposer_A, OEM_A). Moreover, the interviewees agreed that battery legislation does not consider circular economy principles. As Director_Repurp_A suggested*, "when it comes to battery legislations, they jump straight from use to recycle, and there is no reuse in the middle"*. The interviewees mentioned that to use the battery components for a second-life application, companies need to request additional battery components approvals and transport approvals (OEM_A, Remanufacturer_A, Repurposer_A).

Technology and Infrastructure

Two of the most important technology and infrastructure barriers identified in the case studies were the infrastructure investment (ScrapCarRecycler_A, Recycler_A) and the technical skills of the workforce (OEM_A, ScrapCarRecycler_A, Recycler_A). The technically skilled workforce barrier identified from the interviews was related to the unfamiliarity of the workforce dealing with lithium-ion batteries (OEM_A, ScrapCarRecycler_A, Recycler_A). The interviews suggest that dealing with EV batteries at any stage of EoL management requires unique expertise and specialised high-voltage training, which is also a legal requirement (OEM_A, ScrapCarRecycler_A, Recycler_A). Another technology and infrastructure barrier identified was the high infrastructure investment required to process lithium-ion batteries. The interviewees from ScrapCarRecycler_A and Recycler_A argued that they must adapt their facilities to process EV batteries safely. EVs and EV batteries cannot be close to each other to avoid safety hazards.

Knowledge

The lack of information available on the batteries' internal design affects the companies' understanding of the batteries, the work that can be done with the batteries and the amount of material that can be recovered (Remanufacturer_A, Recycler_A). As some of the interviewed companies suggested, the battery manufacturers and OEMs are not sharing information about the batteries’ configuration or Bill of Materials (BoM) (Remanufacturer_A, Recycler_A). Moreover, they are not receiving any guidelines on handling, disassembling, measuring the SOH of batteries, and maximising the value recovery of battery components. As the interviewees explained, they cannot easily contact battery manufacturers to request information about battery design, handling, and testing guidelines since most EV manufacturers buy batteries from other countries and regions. Moreover, in the case of Recycler_A, the lack of information about the batteries' composition makes the chemistry sorting difficult. Manager_Recycler_A explained that the chemistry information is important to separate the modules by chemistry more easily and increase the percentage of material recovered. Similarly, when companies such as Remanufacturer_A do not have information about the batteries' optimal performance, the battery testing becomes inaccurate.

7.3. The perceived influence of drivers on EoL RSC elements and future sustainability supply chain strategies

The analysis of the case studies suggests that the drivers identified (market, economic, policy and knowledge drivers) strongly influence the design of the EoL EV batteries RSC and the future sustainability strategies of the main RSC actors.

Market drivers and EoL RSC elements

According to the study findings, changes in the market, such as the evolution of the automotive sector, influence how the EoL EV batteries RSC is designed (OEM_A, Recycler_A and Repurposer_A). The electrification wave in the industry drives car manufacturers and EoL service providers to adapt their processes and business relationships to develop an RSC that is able to satisfy the increasing demand. The ongoing changes in the automotive industry as well are going to influence the future sustainability strategies that the main actors of the EoL EV battery industry will develop. For instance, Manager_OEM_A explained that OEM_A is planning to stop depending on lithium-ion batteries and they are planning to use different battery energy storage systems such as hydrogen fuel like other OEM_A competitors. As explained by Manager_OEM_A, a change in the EV energy storage system would imply a radical change in the EoL RSC design and the EoL RSC supply chain strategies, which will need to adapt to the automotive sector context and industry needs.

Economic drivers and EoL RSC elements

Economic drivers affect how the EoL processes and business relationships are established and directly affect the companies' future sustainability strategies. The economic drivers have a strong effect on the way the EoL processes are defined and relationships are built. According to the interviewees, the EV battery recovery processes must be efficient and economically viable to be competitive. For that reason, some of the intervieweed companies (OEM_A, Remanufacturer_A, Recycler_A) are developing pilots with research institutes and manufacturing consultancy firm to make an economic assessment of the recovery processes of lithium-ion batteries. Moreover, since the current volume of returned batteries in this initial stage is still low, some companies, such as OEM_A, rely on business relationships with other RSC actors like RecyclerEurope_A with greater economies of scale to process EV batteries. The economic incentives will also affect how the RSC actors' sustainability strategies are defined. According to the case studies findings, economic drivers are encouraging sustainability strategies such as collaboration between companies to develop a full Eol EV battery management service.

Policy drivers and EoL RSC elements

Policies such as the ELV regulations and battery regulations significantly affect the EoL RSC processes since they suggest the responsibilities for the EoL management of EVs and EV batteries, the processes that need to be followed, and recovery targets. The EoL processes identified in the case studies, such as collection, handling, assessment, recovery and battery and material treatment, are significantly motivated by ELV regulations and batteries and waste batteries regulations. As the regulations related to vehicles and batteries are expected to continue changing, the interviewees suggest that future sustainability strategies must be aligned with the current and future policy requirements (OEM_A, Repurposer_A). For instance, companies like OEM_A and Repurposer_A are well aware that according to the new batteries regulations, batteries will need to include battery passports, and they are considering including them in future battery designs.

Knowledge drivers and EoL RSC elements

The capabilities and expertise of the case study companies were shown to have a strong influence on the EoL RSC design by affecting the way the EoL processes are defined. ScrapCarRecycler_A, for instance, is offering training to the personnel of some of the ATFs of their network to process EVs that already have experience processing ICE vehicles. ScrapCarRecycler_A is not looking to find ATFs that process EVs; they are instead investing in training its current ATFs to support them in developing capabilities to handle EVs and EV batteries.

The companies' knowledge also affects how business relationships are built and sustainability strategies are defined. Depending on the need for certain capabilities, some companies are building relationships and collaborating with other companies to gain these capabilities externally (OEM_A with RecyclerEurope_A). OEM_A, for instance, has a partnership with RecyclerEurope_A to gain its EV battery collect and recycling capabilities. Other companies such as Recycler_A aim to gain an EV battery dismantling and sorting capability, which is not Recycler_A's expertise, by collaborating with Remanufacturer_A or similar companies to receive battery cells ready to recycle.

Table 7.1. presents an overview of the drivers for implementing environmental strategies and their perceived influence on EoL RSC and Sustainability Strategies with three categories: Strong Positive influence, Positive influence and no evidence of influence.

Table 7.1. Influence of Drivers on EoL RSC and Sustainability strategies

	EOL RSC		
Drivers for the Development of environmental strategies	**EoL processes**	**Business Relationships**	**Sustainability strategies**
Market	**(+)**	**(+)**	**(+)**
Industry evolution	(+)	(+)	(+)
Competitive advantage	(+)	(+)	(+)
Economic	**+**	**(+)**	**(+)**
Business opportunity	+	(+)	(+)
Value recovery	+	(+)	(+)
Policy	**(+)**	**n.e.**	**(+)**
ELV management legislations	(+)	n.e.	(+)
Product Design legislations	(+)	n.e.	(+)
Battery regulations	(+)	n.e.	(+)
Knowledge	**+**	**(+)**	**(+)**
Operational capabilities	+	(+)	(+)

Legend:
(+) Strong Positive influence
' + Positive influence
n.e No evidence of influence

7.4. The perceived influence of barriers on EoL RSC elements and future sustainable supply chain strategies

As explained by the interviewees, the barriers such as policies, technology and infrastructure strongly influence the design of EoL RSC for EV batteries. According to the findings, the policies favour certain recovery alternatives. Moreover, technological and infrastructure availability and costs limit the EoL process performance. It was also identified that these barriers also constrain the sustainability strategies of the main EoL RSC actors.

Policy barriers and EoL RSC elements

Policies can strongly influence the RSC processes and future sustainability strategies. As the interviewees explained, current battery and waste battery policies favour recycling over remanufacturing or repurposing batteries, making it more difficult for companies interested in remanufacturing and repurposing to do pilots and assess its commercial viability in the UK. According to the interviewees, current battery and waste battery regulations are affecting the development of EoL processes (OEM_A, Repurposer_A). As identified in the OEM_A case study, current battery legislation adds complexity and non-value-added time to the EoL processes. For instance, according to the legislation, getting additional components and transport approval to use battery components in a second life is necessary. The analysis of the case studies suggests that battery regulations are expected to promote several sustainability strategies in the EOL RSC for EV batteries; however, at the same time, current regulations discourage some sustainability strategies, especially the ones that favour second-life applications (OEM_A, Remanufacturer_A, Repurposer_A).

Technology and infrastructure barriers and EoL RSC elements

According to the case study analysis, the technical skills of the workforce and infrastructure investment directly influence EoL RSC design and future sustainability strategies. The workforce's skills and infrastructure will limit the EV EoL RSC configuration and what sustainability strategies can and cannot be implemented (ScrapCarRecycler_A, Recycler_A, OEM_A).

Regarding the technical skills of the workforce, as some of the participants suggested (ScrapCarRecycler_A, Recycler_A, OEM_A), if the staff of a certain facility are not trained to do high voltage work, they cannot process EV batteries at those facilities. ScrapCarRecycler_A, for instance, has nearly 20 ATFs of the total 300 ATFs in their network capable of processing electric vehicles. However, ScrapCarRecycler_A continue offering EV dismantling training to the staff of ATFs to expand their EV-specialised network. On the other hand, OEM_A is assessing which dealers in their network are the most appropriate to process EVs to provide them with the appropriate high-voltage training. As for the infrastructure investment, space availability was identified as a problem for authorised treatment facilities in the city centres since they cannot expand their facilities. Moreover, companies such as Recycler_A do not have enough space for dismantling or discharging. For that reason, they are looking to outsource those processes to other business partners.

Knowledge barriers and EoL RSC elements

The case study findings suggest that the lack of information on the batteries' internal design affects their recovery process and sustainability strategies. The Remanufacturer_A director suggested that the lack of information about battery design is due to a problem of information sharing in the supply chain. Some of the companies (Remanufacturer_A, Recycler_A) shared that the limited knowledge about the internal design of batteries affects the disassembling and testing process. When companies do not receive enough information about the internal design, the disassembling process becomes time-consuming and destructive and can even damage the battery and components internally. Not having information about the battery's internal design leads to incorrect manipulation because the internal components of the battery are not easily accessed, and the personnel that does the disassembling of the battery have to separate components that are welded.

Therefore, the lack of information available about the batteries' internal design and components (e.g. modules, cells) strongly influence the EoL processes since, with limited information, the EoL processes become inefficient, and the value recovered from the batteries gets reduced.

Table 7.2. presents an overview of the barriers to implementing environmental strategies and their perceived influence on EoL RSC and sustainability strategies, which have five categories: Strong positive influence, positive influence, strong negative influence, negative influence, and no evidence of influence.

Table 7.2. Influence of barriers on EoL RSC and Sustainability strategies

	EoL RSC		**Sustainability strategies**
Barriers to the development of environmental strategies	**EoL processes**	**Business Relationships**	
Policy	**(-)**	**n.e.**	**(-)**
Battery regulations	(-)	n.e.	(-)

Dangerous waste transport legislation	(-)	n.e.	(-)
Technology and Infrastructure	**-**	**(+)**	**(-)**
Technical skilled workers	**-**	(+)	(-)
High infraestruture investment	**-**	(+)	(-)
Knowledge	**(-)**	**n.e.**	**(-)**
Lack of information sharing	(-)	n.e.	(-)

Legend:
(+) Strong Positive influence
+ Positive influence
(-) Strong Negative influence
- Negative influence
n.e No evidence of influence

7.5. EoL RSC elements – EoL processes and Business relationships

7.5.1. EoL processes

Collection

One of the first processes that take place in the EoL RSC for EV batteries is the collection of EV batteries from the market through the ATF network and dealers.

For the batteries that arrive at the ATFs, firstly, the EV collection is organised by scrap car recycling companies like ScrapCarRecycler_A. When EV users and car manufacturers hire scrap car recycling companies to scrap EVs, the scrap car recycling company is responsible for referring the vehicle to the nearest ATF of their network prepared to handle EVs for car scrapping and EV battery removal. Removing batteries from EVs requires specialised training to safely dismantle, isolate and finally remove the battery. In addition, another requirement necessary to remove the batteries that is not necessary for ICE vehicles is to follow the IDIS (International Dismantling Information System), guidelines. As explained by Manager_SCR, there has been some progress related to the EV dismantling information sharing with IDIS (International Dismantling Information System), a central repository of treatment information for EVs. The information in the system is gathered from manufacturers from all over the world. This initiative has helped ATFs with the battery removal process; however, there is still valuable information about the internal dismantling of batteries that is not shared by battery designers and could help to improve the EoL processes and make them more efficient (Remanufacturer_A, Recycler_A).

As explained by Manager_OEM_A, in the case of OEM_A, the EV batteries cannot be received by all dealers. Manager_OEM_A argue that most of the personnel of the dealers were not trained nor had the certification to do high-voltage work. Hence, they cannot remove the batteries from the EVs.

Once the batteries have been removed from the EVs, ATFs and dealers can request the collection of the battery from a specialised company to process the batteries and components. Companies such as RecyclerEurope_A work with LSPs in each country to collect the batteries from ATFs and Dealers to take them to its recycling plant. To arrange the collection of batteries in Europe, ATFs and Dealers need to complete in a system the information related to the batteries and their conditions to arrange the transport and send safe packing for batteries if necessary. In the case of the UK, the UK LSP is collecting batteries and storing them temporarily in warehouses until they gather enough batteries to make a full load to the European recycling facility. Due to Brexit, the notification process to send batteries that are considered hazardous is not straightforward anymore. It can take up to five months, causing the stockpiling of batteries in the UK.

Inspection/Disassembling/Testing

The analysis of the case studies suggests that Remanufacturer_A, Recycler_A and Repurposer_A perform some of the inspection, disassembling and initial testing activities.

According to the case studies findings, the inspection process is conducted by Remanufacturer_A, Recycler_A and Repurposer_A. Remanufacturer_A and Recycler_A are currently doing a battery inspection and discharging to ensure the batteries are safe to manipulate and avoid any shortcuts. In the case of Repurposer_A, they do not inspect the whole battery pack; they only do a visual inspection of cells.

After the battery inspection and discharging, Remanufacturer_A and Recycler_A have to do an initial disassembling of the battery up to module or cell level (depending on their needs). According to the interviews, Repurposer_A is not planning to disassemble in-house; they expect to receive the batteries already disassembled to the cell level. The interviewees explained that the disassembling process must be conducted carefully to avoid damaging the modules and cells. In contrast, the disassembling process for recycling does not need to be too cautious. After disassembling the batteries to module or cell level, the modules and batteries aimed for remanufacturing/refurbishing and repurposing need to be tested to measure their correspondent SOH and assign them to their correspondent EoL route.

The analysis of the interviews suggests that the battery dismantling, and battery testing process are the most challenging processes for the case study companies Remanufacturer_A, Recycler_A and Repurposer_A. The dismantling of batteries is currently done by hand and is time-consuming. As the batteries have different configurations, the operators must identify the best way to safely dismantle each battery. The dismantling process requires using different tools to remove the valuable components while dealing with internal adhesives. As Manager_Recycler_A suggested, *"you've got to be really careful with the force that you put on (when dismantling)... or you can rip cells open …it just adds complexity and more time to do it"*.

Regarding the testing process, as the interviewee from Remanufacturer_A suggested, there is no standard testing process; it needs to be flexible. The testing process needs to be flexible to trial and conduct multiple tests to measure the SOH of batteries of different brands and designs with different specifications.

Recycling

One of the most popular EoL alternatives for EV batteries is recycling. Currently, most of the returning EV batteries in the UK are sent to recycling plants in mainland Europe. However, some recycling companies in the UK are developing processes for lithium-ion battery recycling. One of those recycling companies is Recycler_A. Recycler_A is currently working on pilots to process lithium-ion batteries. Some of the activities performed by Recycler_A besides the battery discharging and dismantling of modules to the cell level is material recycling through mechanical and sub-chemical processes to recover copper, plastic, and cathode powder.

As explained by the case studies participants ScrapCarRecycler, Recycler_A and OEM_A, the number of returning EV batteries from the UK market is currently low. Therefore, the number of EV lithium-ion batteries sent for recycling is still small. Companies such as Recycler_A are planning to use their recycling plants initially to process lithium-ion batteries from portable devices such as mobile phones and laptops. Then, they will specialise in electric vehicle batteries as the volume of returned batteries increases in the following years.

Remanufacturing/Refurbishing

Remanufacturing and refurbishing are other EoL alternatives for EV lithium-ion batteries identified in the case studies. Remanufacturing and refurbishing are common practices in the automotive industry. Remanufacturer_A has been remanufacturing/refurbishing petrol and diesel engines and transfer boxes of cars during the last decades. During the last few years, Remanufacturer_A has been developing specialised EV battery remanufacturing and refurbishing programs.

Battery remanufacturing refers to the process by which a battery can be rebuilt and its components repaired and replaced to return the battery to its OEM initial performance automotive specification. Whereas refurbishing follows a similar process to remanufacturing, but the difference is that the battery at the end of the process does not return to the original OEM specification (less than 100% SOH); however, it can still be used for automotive use with a lower warranty period.

Companies such as Remanufacturer_A are developing pilots to assess the feasibility of remanufacturing and refurbishing EV batteries. After the initial battery inspection and the diagnosis of the SOH of the battery, according to the diagnosis results, the batteries that cannot be directly refurbished or remanufactured are dismantled for harvesting. Harvesting in the remanufacturing context means dismantling battery parts that can still be used and keeping them as spare parts for remanufacturing/refurbishing. If the SOH diagnosis results suggest that the battery can be refurbished/remanufactured, the necessary parts of the battery are disassembled, repaired, exchanged and assembled again to get the battery into the desired condition. According to the interviewees, all these activities are conducted manually, following different procedures depending on the battery brand and type. Then, the battery pass by a final battery pack testing to determine the final SOH of the refurbished/remanufactured battery.

Repurposing

The final EoL alternative identified in the case studies is repurposing. Repurposing an EV battery refers to using the battery or its parts, such as modules and cells, to build a new battery that can be used for a different energy storage application. Repurposer_A is a company developing pilots to produce repurposed EV lithium-ion batteries into new ones. The batteries produced by Repurposer_A can be used for small energy storage applications and solar energy storage systems for residences and other commercial applications. After the cells pass a visual inspection and cell grading to assess the SOH of the cells, the cells that pass the test can be used to assemble a new repurposed battery. The battery assembling process developed by Repurposing_A is much more straightforward and less time-consuming than assembling a regular lithium-ion battery. Due to the design of Repurposer_A batteries, the operators do not need to add welding to fix the components. The modular design of the battery allows the operators to insert the cells in their assigned space easily. After that, the new repurposed battery should pass a final battery pack testing to asses that the final SOH is within the desired limits.

7.5.2. Business relationships

Most of the main UK-based RSC actors do not have any type of partnership in place with each other. The only company two companies that have contracts with EV manufacturers are ScrapCarRecycler_A (UK-based) and RecyclerEurope_A (Not UK-based but offers services to the UK market)

In the case of ScrapCarRecycler_A, this company previously had contracts with car manufacturers to scrap their internal combustion engine vehicles. Now these contracts have been updated to include EVs. According to the interviewees, UK-based material recyclers, remanufacturers, and repurposing companies have no contracts with EV manufacturers to process their EV batteries. However, Remanufacturer_A has experience working with car manufacturers and dealer service centres when they used to process other vehicle components such as engines and gearboxes.

Some key partnerships were identified in the case studies. A partnership was identified between ScrapCarRecycler_A and the different ATFs of their network. This partnership allows ScrapCarRecycler_A to have access to more than 300 ATFs locations to serve their clients. As explained by Manager_SCR at ScrapCarRecycler_A, *"we are compromised to instruct and train the ATFs workforce to help them develop capabilities to handle EV batteries"*. By developing the ATFs EV capabilities, ScrapCarRecycler_A gains a competitive advantage because ScrapCarRecycler_A can expand its EVs ATF network and get closer to its clients.

Another important partnership identified is the partnership between Repurposer_A and University_A. University_A is giving valuable support to Repurposer_A on research and development. University_A supports Repurposer_A to make their processes more circular and make the cells assessment process more efficient.

An additional new relationship identified was the relationship between Repurposer_A and international organisations. Repurposer_A is working with several international organisations and receiving grants from them to offer them energy solutions. This grant-based work is allowing Repurposer_A to test their energy solution using waste cells in the field and identify the potential commercial opportunity for their batteries.

The case study companies have demonstrated that they are aware that their companies need to build relationships with other RSC actors and stakeholders to acquire specialised industry capabilities and get greater benefits by working together.

7.6. The linkages between EoL processes, business relationships, Sustainability strategies and EoL RSC sustainability

The EoL processes identified in the case studies have a strong influence on the sustainability strategies of the RSC for EV batteries. Without efficient processes, the EoL RSC cannot be sustainable over time. At the same time, it was identified that business relationships directly influence the sustainability of supply chains since some collaboration practices can increase the efficiency of the processes and make them more sustainable.

One of the issues that emerge from the findings is that some of the processes, such as the dismantling of EV batteries and components, are done manually and do not follow a standardised process, which makes them time-consuming and expensive due to the amount of labour hours assigned to the activities (Remanufacturer_A, ScrapCarRecycler_A, Recycler_A).

Similarly, the testing process is not standardised and requires creating a specific sequence and following different steps for each type of battery (Remanufacturer_A). In the case of the cell testing conducted by Repurposer_A, the testing is a bottleneck that needs to be addressed to improve its throughput. According to the case study findings, the operational cost to process batteries at their EoL is currently charged to car manufacturers. As the interviewees shared, looking at the future high volumes of returning batteries, the companies involved in the EoL management of EV batteries need to increase their capacity and increase the efficiency of their processes to make their businesses economically viable and sustained over time. In addition, the processes like dismantling need to be adapted to increase the volume of components and materials recovered and improve the processes' environmental sustainability.

The analysis of the interviews suggests that the business relationships can lead to the development of sustainability strategies to improve the economic and environmental sustainability of the RSC.

Some case study companies plan to build partnerships and collaborate with other RSC actors to improve the sustainability of their operations. By building strong partnership relationships and collaborating with other RSC actors and stakeholders to improve their RSC processes. Some of the examples may be found below:

- **SE1:** Companies involved in the recovery stage (i.e. Remanufacturing, Repurposing, Recycling) of the EoL management of batteries aim to increase the number of batteries collected from the market by building a partnership with

Scrap Car Recycling companies that have access to a wide ATF network that will receive the returning batteries (Remanufacturer_A, Recycler_A).

- **SE2:** One of the case study companies plans to share facilities and do a logistical integration with other RSC actors to reduce operational and transport-associated costs, time, and safety hazards (Remanufacturer_A). For instance, as the manager of Remanufacturer_A suggested, remanufacturers will always end up having components and materials they cannot use that can be sent directly for recycling.
- **SE3:** By working with UK battery manufacturers, remanufacturers could improve information sharing with UK battery assemblers and have access to disassembling and battery SOH information to improve their processes.
- **SE4:** Develop a full EoL EV battery management service solution (ScrapCarRecycler_A, Recycler_A, OEM_A). A full EoL EV battery management service solution would imply that OEMs would only need to hire one single company that will be responsible for ensuring collection, inspection, disassembling, testing, and recovery options desired (Remanufacturing/Refurbishing, Repurposing, Recycling). Some of the case study companies shared their interest in collaborating with companies involved in the RSC of EV batteries to contribute with their unique expertise and capabilities, avoid engaging in activities that are not specialised, or avoid doing activities they do not have the technology or infrastructure to perform. These collaboration strategies are expected to have a positive economic and environmental influence on the RSC, helping to improve its sustainability.
- **SE5:** Other interviewees also shared that they could improve their sustainability by collaborating with stakeholders external to the EV battery supply chain (Repurposer_A). The interviewees from Repurposer_A shared that they are collaborating with a University to improve the efficiency of their testing process and increase their throughput.

Some of the companies also argued that the key to a sustainable supply chain is innovation in the business model. Some innovation sustainability strategies.

- **SE5:** Director_Reman_A, for instance, suggested that it will be possible in the future to pay OEMs for their batteries if they manage to get a profit from the second-life applications of the batteries or sell components and materials.
- **SE6:** Repurposer_A argue that they want to shift their business model completely. As Director_Repurp_A suggested, they currently build batteries. However, the company is looking to facilitate companies to build their batteries in

the future. Repurposer_A is planning to license the technology and tools for assembling and repurposing batteries, share the information of the Battery Management System, and introduce levels of traceability (servicing, EoL routes).

Table 7.3. presents an overview of EoL process, business relationships and their influence in Sustainability Strategies that have three categories: Strong Positive influence, Positive influence, and no evidence of influence.

Table 7.3. Influence of EoL processes and business relationships on Sustainability strategies (Author, 2024)

	Sustainability strategies	
EoL processes	**Innovation**	**Collaboration**
Collection	n.e.	(+)
Inspection/Disassembling/Testing	(+)	(+)
Recycling	n.e.	(+)
Remanufacturing/Refurbishing	(+)	(+)
Repurposing	(+)	(+)
Business Relationships	(+)	(+)
Partnerships among supply chain members	(+)	(+)
Partnership with supply chain external stakeholders	(+)	(+)

Legend:
(+) Strong Positive influence
+ Positive influence
(-) Strong Negative influence
- Negative influence
n.e No evidence of influence

7.7. Revised Framework and propositions

7.7.1. Revised Framework

In this research, the NRBV and its three path dependency strategies (i.e.Pollution prevention, product stewardship and sustainability development) (Hart, 1995) were used to structure and guide the study of the EoL RSC for EV batteries and understand how to make it more sustainable.

The framework used in this research has three main constructs: Drivers and barriers to implementing environmental strategies, Reverse supply chain design and Sustainable

Reverse supply chain. NRBV theory helped to analyse the particular case of the EoL RSC for EV batteries that, unlike previous industries studied (Masoumik *et al.*, 2014; Miemczyk, Howard and Johnsen, 2016; Ashby, 2018) is in a developing stage. The findings of the cross-case study suggest that the drivers for implementing environmental strategies the RSC processes, business relationships, influence sustainability strategies. Meanwhile, the barriers negatively influence RSC processes and sustainability strategies. At the same time, RSC processes and relationships positively influence sustainability strategies. The perceived influence between the different elements of the conceptual framework construct is presented in Figure 7.1.

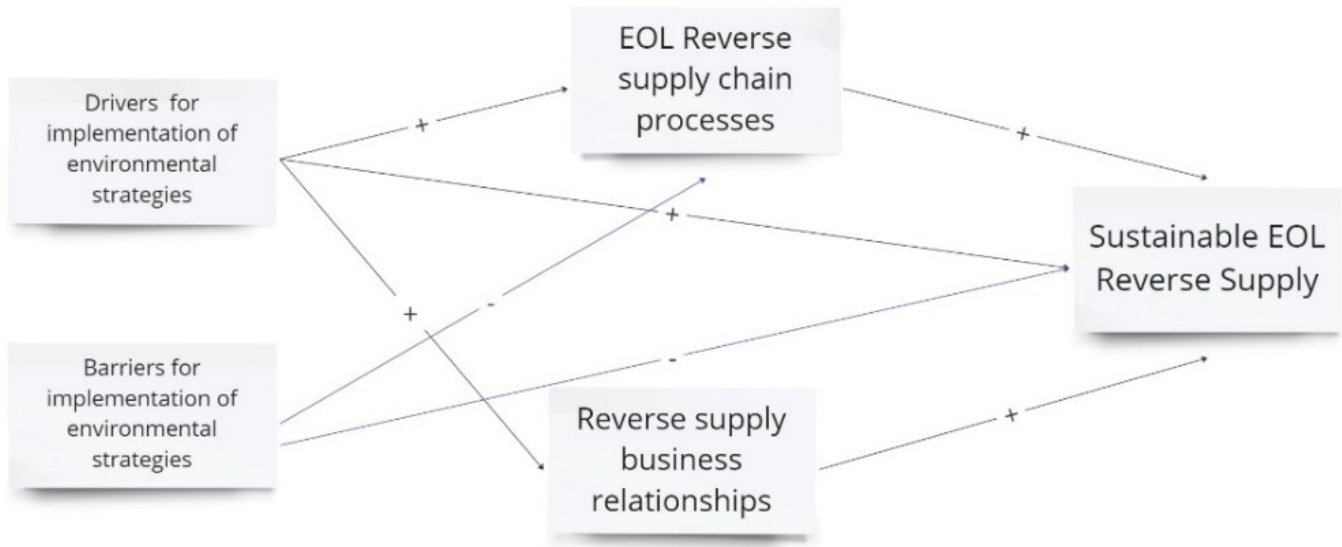


Figure 7.1. The revised conceptual framework

Based on the cross-case study analysis, the influence of the different framework constructs was identified. A detailed summary of the drivers and barriers to the development of environmental strategies and their perceived influence on EoL processes, business relationships and sustainability strategies can be found in Table 7.4. The influence of the drivers and barriers in the EoL RSC and Sustainability strategies has been categorised as Strong Positive influence, Positive influence, Strong Negative influence, Negative influence and No evidence of influence.

	EoL RSC		**Sustainability strategies**
	EoL processes	**Business Relationships**	
Drivers for the Development of environmental strategies			
Market	**(+)**	**(+)**	**(+)**
Industry evolution	(+)	(+)	(+)
Competitive advantage	(+)	(+)	(+)
Economic	**+**	**(+)**	**(+)**
Business opportunity	+	(+)	(+)
Value recovery	+	(+)	(+)
Policy	**(+)**	**n.e.**	**(+)**
ELV management legislations	(+)	n.e.	(+)
Product Design legislations	(+)	n.e.	(+)
Battery regulations	(+)	n.e.	(+)
Knowledge	**+**	**(+)**	**(+)**
Operational capabilities	+	(+)	(+)
Barriers for the Development of environmental strategies			
Policy	**(-)**	**n.e.**	**(-)**
Battery regulations	(-)	n.e.	(-)
Dangerous waste transport legislation	(-)	n.e.	(-)
Technology and Infrastructure	**-**	**(+)**	**(-)**
Technical skilled workers	-	(+)	(-)
High infrastructure investment	-	(+)	(-)
Knowledge	**(-)**	**n.e.**	**(-)**
Lack of information sharing	(-)	n.e.	(-)

Legend:
(+) Strong Positive influence
+ Positive influence
(-) Strong Negative influence
- Negative influence
n.e No evidence of influence

Table 7.4. Driver and barriers to the development of environmental strategies and their perceived influence in EoL RSC and sustainability strategies

The case studies findings suggests that the electrification of the automotive industry is disrupting the industry at a manufacturing level and across its whole supply chain. As

Randall (2016) suggested, batteries are a key new element of electric vehicles (Randall, 2016). In the case of the EoL EV battery Reverse supply chain actors, according to the study findings, key automotive suppliers such as scrap car recyclers, remanufacturers that provided services to ICE vehicles have been forced to adapt their processes and services to be able to receive and process electric vehicles and batteries. In addition, the electrification of the automotive industry has been an opportunity for companies such as precious metal recovery recycling companies to expand their market to include the automotive industry (Recycler_A). Similarly, new companies are developing repurposing services to support the EoL management of EV batteries (Repurposing_A).

The shift in the automotive industry has created new business opportunities in the EoL management sector. EV batteries are classified as hazardous goods that cannot be disposed of at their EoL. Moreover, as was expressed in the literature (Klör, Bräuer and Beverungen, 2014; Canals Casals, Amante García and Cremades, 2017; DeRousseau *et al.*, 2017; Olsson *et al.*, 2018) and in the case studies of this research (Repurposer_A, Remanufacturer_A, Recycler_A) batteries hold high value at their EoL that can be reused and components and materials that can recycled.

Regarding policies, aligned with previous research (Govindan and Bouzon, 2018; Govindan and Hasanagic, 2018; Narimissa, Kangarani-Farahani and Molla-Alizadeh-Zavardehi, 2020), policies were found to be both a driver and a barrier to the development of a reverse supply chain for products. ELV regulations and battery regulations such as *Regulation (EU) 2023/1542 of the European Parliament and of the Council concerning batteries and waste batteries* that had been released in July 2023 (European Commission, 2023) promote an environmentally friendly EoL management of EVs by defining responsibilities for the EoL management of EVs and EV batteries, the processes that need to be followed, and collection targets. However, as was identified in the case studies, the study participants agreed that battery policies favour recycling, which is the least circular economy strategy and does not promote the second-life applications of batteries and components. The new *Regulation (EU) 2023/1542 of the European Parliament and of the Council concerning batteries and waste batteries* (European Commission, 2023) mentions that batteries can be repurposed and remanufactured. According to the latest battery regulation, repurposed and remanufactured batteries should comply with the *Directive (EU) 2019/771 of the European Parliament and of the Council on contracts for the sale of goods* (European Commission, 2019). However, according to the case study findings, approvals to ship and use each of the batteries' components in the UK aftermarket are still complex and take long periods of time.

Aligned with previous literature on the EoL management of batteries, the technical skills of the workforce and infrastructure investment were also identified as key barriers to developing the RSC for EV batteries (Lisbona and Snee, 2011; Zeng, Li and Liu, 2015; Rohr *et al.*, 2017). The study findings suggest that the handling and treatment of EV batteries requires staff with high voltage skills and training, which was not required previously with ICE vehicles (Repurposer_A, Remanufacturer_A, ScrapCarRecycler_A). Hence, as identified in the case studies (ScrapCarRecycler_A, Recycler_A), some companies are working towards developing this capability across the RSC of EV batteries. Regarding infrastructure investment, the lack of space availability was pointed out as one of the main problems because EVs and their corresponding EV batteries require wider spaces than ICE vehicles to operate safely.

Another key barrier identified was the lack of information sharing across the EV battery supply chain. Previous research has appointed information sharing between supply chain actors as a crucial element for the development of sustainable closed-loop supply chains (Mehrjerdi and Shafiee, 2021). In this research product design/handling information and product performance were identified as crucial information for the EoL management of EV batteries. Unlike other products, defining and setting up the processes for handling and recovering electric vehicle batteries and components requires a deep knowledge of the internal design of the product and handling guidelines. As the study participants suggested, when they receive a battery to be processed, they have limited information about the Bill of material (BOM), product design, handling, disassembling, state of health (SOH) (Recycler_A, Remanufacturer_A). Not having information about the bill of material (BOM), product design, handling, and disassembling makes the dismantling process longer and inefficient due to incorrect manipulation affecting the percentage of material recovered.

In addition, the influence of the EoL processes and business relationships on the sustainability strategies in the EoL RSC for EV batteries is summarised in Table 7.5.

Table 7.5. EoL processes, Business relationships and their perceived influence on Sustainability strategies (Author, 2024)

	Sustainability strategies	
EoL processes	**Innovation**	**Collaboration**
Collection	n.e.	(+)
Inspection/Disassembling/Testing	(+)	(+)
Recycling	n.e.	(+)
Remanufacturing/Refurbishing	(+)	(+)
Repurposing	(+)	(+)
Business Relationships	(+)	(+)
Partnerships among supply chain members	(+)	(+)
Partnership with supply chain external stakeholders	(+)	(+)

Legend:
(+) Strong Positive influence
\+ Positive influence
n.e No evidence of influence

Consistent with the literature (Olsson *et al.*, 2018), the study findings suggest that the electrification of the automotive industry is disrupting the automotive supply chains and generating new business opportunities and economic incentives for companies across the industry and some newcomers (Repurposer_A, Remanufacturer_A, Recycler_A, ScrapCarRecycler_A). According to the research findings, a new EV battery EoL RSC is developing in the UK. Companies responsible for collecting End-of-life vehicles are adapting their collection network and preparing to receive EVs (e.g.ScrapCarRecycler_A). To reduce the environmental influence of EV batteries at their EoL, there are companies developing new techniques and running pilots to inspect, disassembly and test EV batteries (Remanufacturer_A, Repurposer_A). The companies developing these techniques aim to remanufacture/refurbish batteries to extend the life of the batteries in the automotive industry, repurpose batteries to extend the life of the cells in second-life applications and recycle valuable components and metals of batteries (Remanufacturer_A, Repurposer_A).

The maturity of the business relationships between car manufacturers and EoL EV battery service suppliers is still in an early stage. Only a few examples of partnerships across the EV battery EoL RSC were identified (i.e. Scrap Car Recycling companies – Car Manufacturers and Recycler – Car manufacturer). However, these contractual relationships started with agreements for ICE vehicles and have been updated to include EVs and EV batteries.

The need to adapt to the electrified future of the automotive industry is motivating the development of new business relationships in the EoL RSC for EV batteries to develop new industry capabilities. As previous research suggested, collaboration in the battery value chain is critical to developing new business models that benefit all the battery supply chain actors (Olsson *et al.*, 2018). Some interesting examples of potential future collaboration were identified in this research. The case study participants expressed their interest in collaborating with other companies involved in the EV battery recovery stage to capture volumes, specialise in their core activities, and obtain technological and operational capabilities across the supply chain (ScrapCarRecycler_A, Recycler_A, OEM_A, Remanufacturer). An interesting collaboration example not discussed in previous research is a collaboration with external supply chain stakeholders such as academic-industry collaboration and industry-nacional/international organisations collaboration. The study findings suggest that some of the companies in the EoL RSC for EV batteries are investing in R&D and building partnerships with universities to improve their battery treatment process and make it more circular (e.g. Repurposer_A - University_A). Companies such as Repurposer_A are working with international organisations to test their energy solutions using second-life batteries (e.g. Repurposer_A - DevelopBank_A). Other companies are building partnerships with recycling associations to train their supplier base to handle EVs and EV batteries (e.g. ScrapCarRecycler_A - British Metals Recyclers Association).

7.7.2. Propositions

The study findings suggest that an efficiency problem across the EoL processes identified in the case studies strongly influences the sustainability of the RSC for EV batteries. As the case study participants suggested, the EoL RSC cannot be economically viable and sustainable over time without efficient processes. According to the findings, the design of a sustainable supply chain will require a context that promotes the development of sustainability strategies. As Winslow, Laux, and Townsend (2018) suggest, waste management regulations are essential to protect human' health and the environment since they provide guidelines about how hazardous and non-hazardous materials should be managed at their EoL. Policies play an important role in setting the context for developing sustainable EoL RSC for EV batteries. The study participants agreed that legislations around the EoL management of batteries (i.e. Directive 2000/53/EC of the European Parliament and of the Council on end-of-life vehicles and Regulation (EU) 2023/1542 on batteries and waste batteries) do not enforce battery design transparency for EoL management purposes (CarManufacturer_A, Remanufacturer_A, Repurposer_A).

As identified in the case studies, companies such as Remanufacturer_A, Repurposer_A and Recyler_A found that disassembling and testing activities are challenging. Disassembling and testing activities are time-consuming and limit the battery's throughput and the amount of material recovered. The disassembling and component/material recovery process of batteries is currently done manually and is complex due to the EV batteries' design characteristics. As identified in the literature (Malinauskaite, Anguilano and Rivera, 2021) and confirmed in the case studies (Remanufacturer_A, Recycler_A), EV batteries have several small components that are glued to the battery packs, making them difficult to remove. The manual process makes the disassembly time-consuming and expensive due to the long labour hours assigned to the activities (Remanufacturer_A, ScrapCarRecycler_A, Recycler_A). As the batteries, modules, and cells have different design configurations, the operators that disassemble them must identify the best way to dismantle them while safely dealing with internal components and adhesives. According to the case study findings, along with the dismantling process, the testing process was also identified as a challenging and time-consuming process that needs to be improved.

The battery and components (i.e. modules, cells) testing process is not standardised and requires creating a specific sequence and following different steps for each type of battery (Remanufacturer_A). Regarding the cell testing conducted by Repurposer_A, as Director_Repurp_A suggested, the testing used in ProjectRep_A has been identified as a bottleneck that needs to be addressed to improve battery production throughput. The findings suggest that the initial SOH information is essential to define the testing process that requires comparing the performance of the received batteries/modules and cells with the State of Health (SOH) conditions at the beginning of their first life (Remanufacturer_A). As the study participants suggested, EV battery manufacturers are currently not incentivised to share batteries and components disassembling information downstream in the RSC (Remanufacturer_A, Repurposer_A). Moreover, information about the performance of EV batteries and components at the beginning of their first life is not shared by EV battery manufacturers with companies involved in the EoL management of batteries. As the study participants suggested, they do not have control over the decisions of battery manufacturers; therefore, they need legislation to support them.

Hence, the first proposition is formulated as follows:

Proposition 1: *In emerging RSCs, regulatory frameworks are needed to ensure manufacturers share critical product information to develop sustainable EoL processes.*

The findings illustrate the need for collaboration in emerging EoL RSC to become sustainable. According to the case study findings, the companies involved in the EoL management of batteries are planning to collaborate with battery manufacturers and RSC stakeholders to address the main issues identified in the EoL process and improve its efficiency.

Currently, China, Korea, and Japan have more than 90% of the global EV battery market (Forbes, 2023), giving the companies involved in the UK EoL management of EV batteries limited access to EV battery manufacturers. In the UK, there is only one open high-scale EV battery producer, Envision AESC, established in 2012 and located in Sunderland, where Nissan Leaf batteries are produced. Envision AESC has almost completed the construction of its new UK large-scale gigafactory in Sunderland and is expected to start operating in 2024 (AESC, 2023). In addition, Tata Group has announced that its group will invest over £4 billion in a UK gigafactory (GOV.UK, 2023c).

As Remanufacturer_A suggested, collaborating with battery manufacturers would be an ideal scenario for them since that would allow them to get easier access to battery designers and access to particular battery information such as disassembling and testing guidelines. Remanufacturer_A is a company that has offered engine and gearbox remanufacturing services to important OEMs in the UK. The participants suggested that the EV batteries they receive from Asia do not follow the design for end-of-life principles. Hence, Remanufacturer_A and Repurposer_A are planning to collaborate with battery manufacturers to be involved in product development and suggest design for end-of-life principles to improve some of the remanufacturing and repurposing processes. As the case study participants suggested, following design for end-of-life principles could help to improve the disassembly process (faster and less destructive), and SOH assessment (faster and more precise) to extend the lifespan of batteries, modules and components.

Moreover, some case study companies suggested they plan to collaborate with companies involved in the RSC of EV batteries that can share their unique expertise and capabilities. Companies involved in the recovery stage (i.e. Remanufacturing, Repurposing, Recycling) of the EoL management of batteries plan to collaborate with Scrap Car Recycling companies with access to a wide ATF network. Building partnerships with Scrap Car Recycling companies will allow the end-of-life management stakeholders to get access to a wide ATF network that will receive the returning EV batteries.

The case study companies understand that EV batteries are dangerous and complex products. Therefore, they want to avoid engaging in activities they are not specialised in or doing activities they do not have the technology, training or infrastructure to perform. The case study companies suggested they plan to develop a full EoL EV battery management service solution (ScrapCarRecycler_A, Recycler_A, OEM_A). A full EoL EV battery management service solution would imply that OEMs would only need to hire one single company that will be responsible for ensuring collection, inspection, disassembling, testing, and recovery options desired (Remanufacturing/Refurbishing, Repurposing, Recycling). Companies like Repurposer_A are also collaborating as a Knowledge Transfer Partnership (KTP)[21] with a university research group to improve testing techniques and associated technologies. The next proposition is formulated as follows:

The next proposition is formulated as follows:

> ***Proposition 2:*** *In emerging RSCs, early supplier involvement and collaboration among EoL RSC parties and stakeholders are required to develop efficient EoL processes.*

According to the case study findings, to have a sustainable EoL RSC for EV batteries, the main RSC actors need a market for recycled materials, remanufactured batteries and repurposed batteries. As Manager_Recycler_A suggested, they have identified potential markets for the material recovered from batteries, such as cathode powder, copper and plastics. However, despite the increasing interest in the remanufacturing and repurposing of batteries evidenced in prior studies that have focused on the technical and economic feasibility of batteries second-life applications (Reinhardt *et al.*, 2019; Schulz *et al.*, 2020; Haram *et al.*, 2021; Al-Alawi, Cugley and Hassanin, 2022), Manager_OEM_A and Director_Repurp_A argue that the market for remanufactured and repurposed batteries market is still uncertain.

Manager_OEM_A suggested that the technology and chemistry of EV batteries are constantly evolving. As Manager_OEM_A explained, the most common battery chemistry is lithium-ion; however, by the time batteries return from the market, OEM may be using batteries with a completely different chemistry in its cars. Therefore, the

[21] Knowledge Transfer Partnerships is a partly government-funded programme to encourage collaboration between businesses and universities (academics and graduates) in the United Kingdom (KTN, 2023)

remanufacturing option could be used to service cars that are still under warranty and have not been in the market for so long. Therefore, there is a potential to develop a market for remanufactured batteries that could be used in the dealers' service centres for servicing electric vehicles.

As Director_Repurp_A suggested, the repurposing market for EV batteries is still in its infancy. However, through the pilots that Repurposer_A is conducting with international organisations, they are proving that their energy storage solutions using repurposed batteries have an economic, environmental and social impact to justify a market. As the study findings suggest, it is crucial to develop pilots in field applications that use repurposed batteries to bring energy storage solutions to different markets, like the ones developed by Repurposer_A in developing countries, to open and secure market opportunities. The last proposition is formulated as follows:

> ***Proposition 3:*** *In emerging RSCs, pilots in field applications are required to test EoL solutions and open market opportunities.*

8. Simulation study analysis and discussion

8.1. Introduction

The case study findings suggest that the companies involved in the EoL management of EV batteries are planning to build partnerships and collaborate with other RSC actors to improve the sustainability of their operations. Therefore, to continue the analysis of the third construct, "Sustainable EoL Reverse supply chain" (Figure 8.1), a supply chain predictive model is proposed to study the impact of sustainability strategies in the EV batteries' EoL reverse supply chain design.

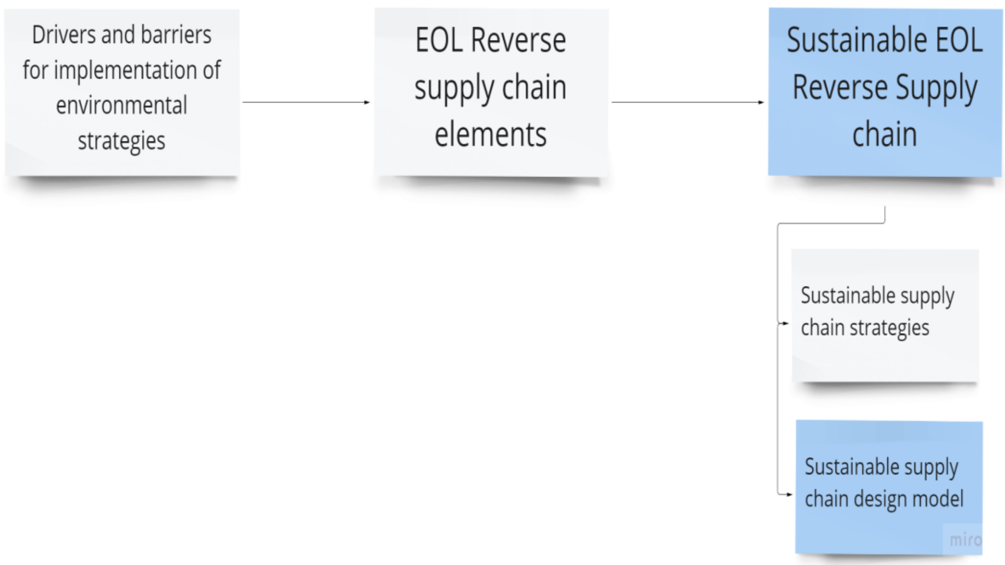


Figure 8.1. Sustainable EoL Reverse supply chain

Modelling a future sustainable EoL reverse supply chain poses different challenges. In the case of the EV battery industry, its UK EoL reverse supply chain is still in a developing stage, and no defined supply chain is currently operating. Also, the EoL routes for EV batteries are not clearly defined yet. The technology for recycling, recovery and remanufacturing is still under development. The service providers and companies that offer EoL services are at the moment handling low volumes of batteries, and markets for the recovered products and materials are still being explored. Moreover, the legislations around the EoL treatment of EV batteries are subject to change. Currently, the legislation focuses mainly on the recycling alternative, not other options such as remanufacturing and repurposing. For these reasons, it is uncertain what is going to happen in the future with UK EoL RSC for EV batteries.

This research draws on the preliminary information collected from managers and directors from companies that have experience providing EoL services to the automotive industry and have worked or have run pilots with EV batteries. This study presents a potential UK EoL supply chain for electric vehicle batteries that includes a Dealer service centre, a specialised ATF network across the UK, a Remanufacturing company, a Repurposing company and a recycling company. These selected companies are key players in the EoL supply chain for EV batteries since they are responsible for collecting the EV batteries from EV users and offer different recovery alternatives to extend the life of EV batteries, components, and materials. All the companies involved in this research are UK-based. The UK was chosen for this research since it is one of the most influential electric vehicle markets in Europe; however, its RSC is developing and requires supporting tools to establish its long-term plans. Even though this study focuses on the UK context, the methodology can be used to study other contexts, and the model can be easily adapted.

Authors like Robinson (2014), Rossetti (2015) and Greasley (2023) have proposed different methodologies to conduct simulation studies. The methodologies proposed by the authors are generally similar but vary in the name of activities and the number of sub-activities. Rosseti (2015), for instance, proposes a methodology that follows four main general steps: Problem formulation, Simulation model building, Experimental Design and Analysis, Evaluate and Iterate, Implementation). Robinson's (2014) methodology outline includes the following steps: Conceptual modelling, Model coding, Experimentation, Implementation. For this research, the simulation study methodology proposed in Greasley (2023) was used as a reference since it was identified as the most appropriate methodology for conducting this thesis simulation and study and complemented with the subactivities presented in Rosseti (2015). A summary of the simulation methodology of this study may be found in Figure 8.2

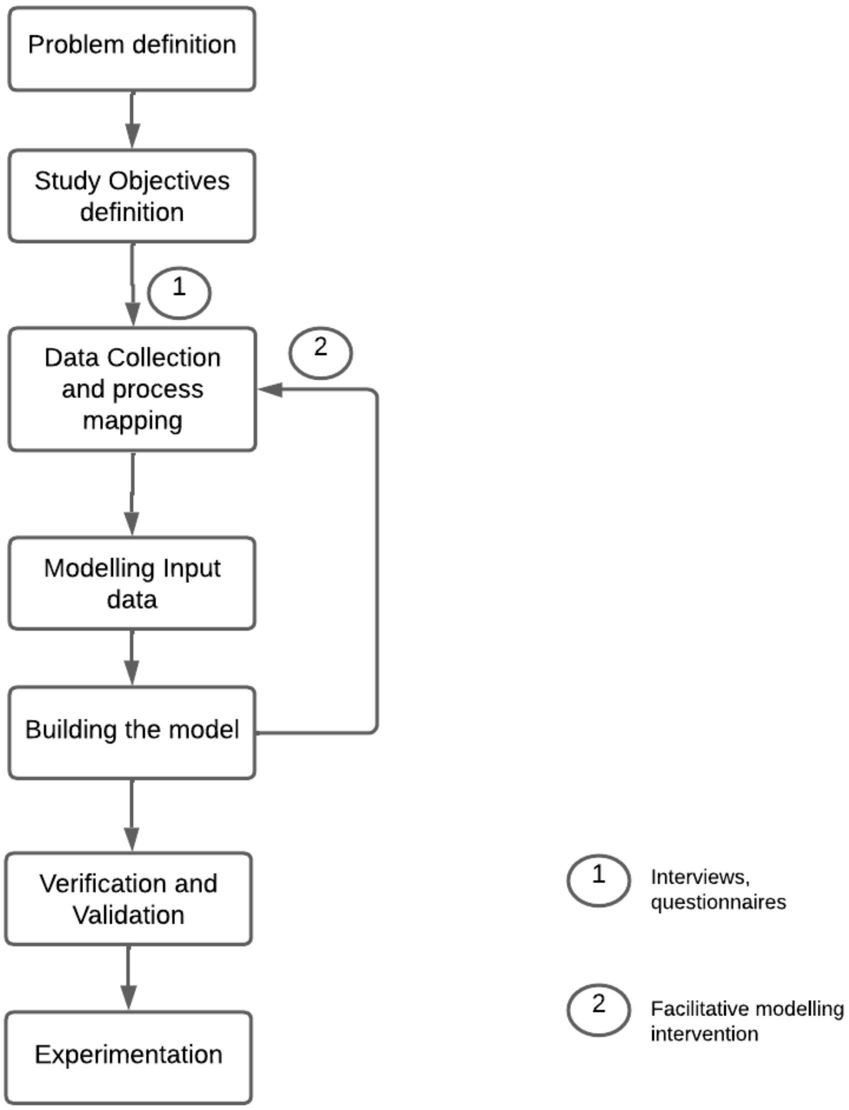


Figure 8.2. Simulation study methodology (Adapted from Greasley, 2023)

8.2. Study objectives, model scope, outputs and inputs

Simulation study objectives

The objectives of this study are the following:

- To build a facilitative simulation model that supports the design of an emerging EoL RSC for EV batteries.
- To run a set of simulated scenarios to explore how different sustainability strategies affect the RSC design configuration, capacity, economic impact (i.e. value of material recovered, production savings), environmental impact (i.e.

batteries recovered, batteries remanufactured, batteries for a second life, kg of materials recovered, CO_2 emissions reduction)

Model outputs to determine the achievement of objectives

- The general capacity of the EoL RSC for EV batteries; specific capacity at the Dealer service centre, ATFs, Remanufacturing company, Repurposing company, Recycling company.
- Utilisation of resources (i.e. staff, machines)
- Results of economic and environmental metrics of the system.
    - **Economic benefits:** value of material recovered, production savings.
    - **Environmental benefits:** batteries recovered, batteries remanufactured, batteries for a second life, kg of materials recovered, CO_2 emissions reduction.

Model inputs (Experimental factors)

- Processing times of activities (disassembling, testing),
- The proportion of batteries sent to recovery facilities (i.e. recycling, remanufacturing, repurposing)
- Future demand levels according to the demand forecast in Appendix III – Forecast OEM EoL Batteries.

8.3. Data collection and process mapping

The initial data of the current process was collected through semi-structured interviews and questionnaires. While the future RSC for EV batteries model was abstracted and refined using facilitated modelling sessions with managers and directors from a scrap car recycling company that manages an important ATF network, Remanufacturing company, repurposing company and a lithium-ion battery recycler. In a section of the unstructured interview (Appendix I -Interview protocol -), the interviewees were asked about the corresponding processes involved in the EoL management of electric vehicle batteries. Meanwhile, the questionnaires (Appendix II -Simulation study questionnaire) were used to collect specific data about the processes such as processing times, sequences, workforce schedules.

The initial data was collected from the companies described below.

(1) Scrap car recyclers are the companies that buy cars from car users as scrap, and to do so, they work with a network of independent Authorised Treatment facilities (ATF). **ScrapCarRecycling_A** was chosen for this research since it has one of the biggest Authorised treatment facility network in the UK that receives EVs and extract their correspondent EV batteries.
(2) **Remanufacturer_A** was chosen for this study within the EV battery remanufacturers in UK. **Remanufacturer_A** has done some refurbishing work in the past and has experience working in some refurbishing and remanufacturing pilot projects with electric vehicle batteries.
(3) Another important actor of the UK RSC for EV batteries that help to extend the life of the EV battery components are repurposing companies. **Repurposing_A** was chosen for this study since it is developing projects to build Lithium-ion batteries for storage applications using used EV battery cells.
(4) **Recycler_A** is a UK-based material recycling company that offers lithium-ion battery recycling services with a dedicated factory area and specialised personnel.

The facilitated modelling session was used to refine the integrated process map of the RSC for EV batteries and refine and validate the simulation model.

The participants of the facilitated interventions were:

- Client_AC: Environmental Planning Manager – Automotive company
- Client_RG: Technology and Innovation Manager – Recycling group
- Client_EC: Company Director – Engineering company
- Client_CF: Head of Forecasting – Consultancy Firm specialised in lithium-ion battery and electric vehicle supply chain.
- Client_CF2: Battery specialist and Senior Engineer from Circular Economy team – Consultancy Firm specialised in circular economy projects.

Before building up the simulation model of the integrated end-of-life supply chain network for electric vehicle batteries, the first step was to map the initial subprocesses performed by each of the companies involved in this study. It is worth mentioning that at the moment of the study the companies interviewed do not have any type of partnership or collaboration agreement in place. These companies are working individually to develop solutions for EoL EV batteries.

Bellow, each of the subprocesses performed by each company that participated in this study are described in detail and a process map that represents the sequence of steps in the process is created.

8.3.1. Subprocess mapping

Current process - ATFs

The current process entails the following steps:

- EVs arrives at the ATF yard and the operators do an inspection to check that nothing happened to the EV while in the transport.
- Then, the operators dismantle EVs following dismantling and safety information on the IDIS (International Dismantling Information System) (IDIS group, 2016) and guidelines provided in previous training. The IDIS is a central repository of manufacturer compiled treatment information for ELVs, with information gathered from manufacturers from Europe, Japan, Korea, Malaysia, India, China and the USA.
- After that, the vehicle is put on ramps so the batteries can be isolated. During the isolation the operator makes sure to drain any coolants, disconnect the battery from the car and remove the safety plug, so the battery is safe to handle.
- Then, the operator removes the EV battery from the vehicle using lifting equipment and label the battery.
- After that, the battery is placed under a high voltage rubber mat in a safe undercover area with plenty of ventilation. Figure 8.3 shows a simplified map that includes the activities performed by the ATF.

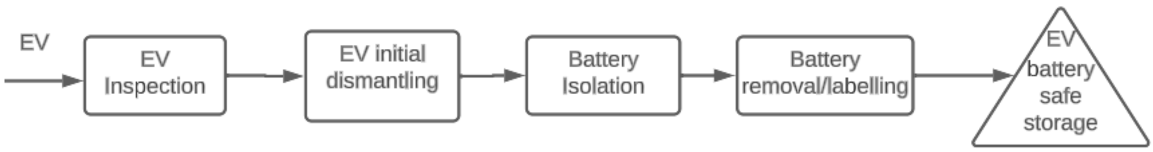


Figure 8.3. ATF process map

Current process - Remanufacturing company

The current process followed by the remanufacturing company entails the following steps (See Figure 8.4):

- When Remanufacturer_A receives batteries from their clients, the first step is to discharge the batteries.
- Then, the battery needs to be isolated by checking if the cooler pipes have come loose or split within the pack because they could cause an electrical shortcut.
- The battery pack then is disassembled manually to module level

- The next step is the diagnosis. The diagnosis of EV batteries is a key step to identify what the faults are, and based on that information, decide where to send the batteries. The diagnosis of the battery involves the measurement of the State of Health (SOH) of the battery modules. After measuring the SOH Remanufacturer_A has identified two initial possible routes.
- The first route would be for good functional batteries that can be either refurbished or remanufactured. Measuring the state of health of a battery is not a straightforward process, and it will vary depending on the brand, model and technology of the batteries.
- The second option for batteries is harvesting. Harvesting in this context refers to gathering the useful parts of products to store them and use them later for remanufacturing. For instance, if there is a battery with 18 modules and one string of 6 modules is fine, and the other two strings are broken, the good string with six modules combined with other useful parts could be used to build a full battery again.
- If the components harvesting, modules should be dismantled to a cell level and prepared for recycling.

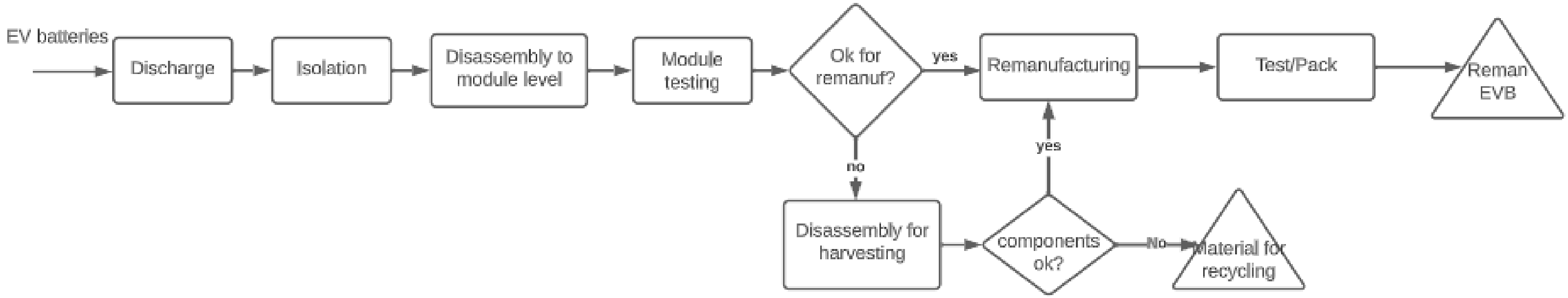


Figure 8.4. Process map Remanufacturing company

Current process - Repurposing company

The current process followed by the repurposing company entails the following steps (See Figure 8.5):

- The process starts when Repurposing_A receives the waste battery cells from suppliers.
- Then, the cells pass through a visual inspection to identify what cells look in good conditions.
- Afterwards, the cells are labelled and loaded to the testing machine.
- Then, the testing machine measures the SOH of the cells and establish their grading category.
- If the battery cells performance is too low they are sent for recycling.
- If the cells have a high performance the cells are sent for the new battery assembly.
- Afterwards, the whole battery pack needs to pass through a final testing. If the battery does not pass the final test the battery pack is disassembled, and the cells are sent to the assembly step again.

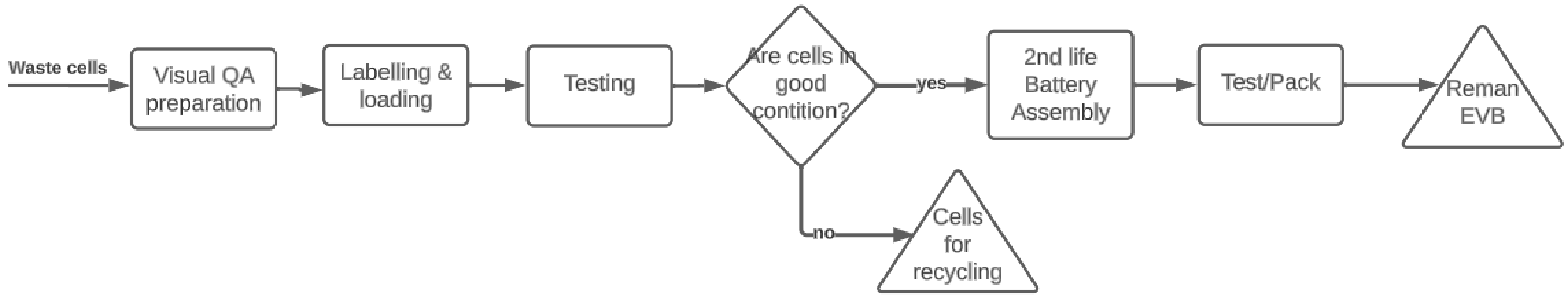


Figure 8.5. Process map repurposing company

Current process - Recycling company

The current process followed by the repurposing company entails the following steps (See Figure 8.6):

- The process begins when Recycler_A receive the EV battery packs.
- Then, the operators make sure that the batteries are discharged.
- The next step is the dismantling process which is done by hand and with the help of specific tools.
- After, the batteries have to be dismantled to a module level.
- Then, the cells are taken out from the modules, and then these are sent to the recycling plant.
- In the recycling plant, the cells are split up
- After, the cells pass through various mechanical and sub chemical processes to separate copper, plastic and cathode powder. On average, Recycler_ A expects to recover 80% of the total weight of the batteries.

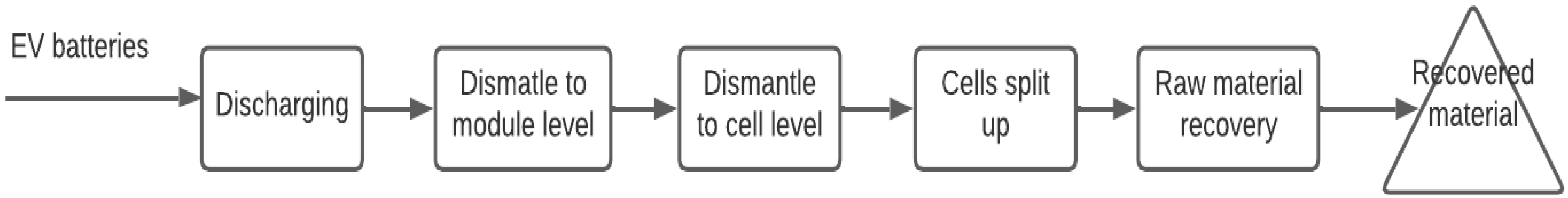


Figure 8.6. Process map Recycling company

8.3.2. Base model overview diagram and logic

Using the initial information of the subprocesses and the case study findings that suggested the development of a collaborative end-of-life management solution for EV manufacturer, the model proposes a future EoL RSC for EV batteries that offers a full end-of-life management solution for a EV manufacturer in the UK.

The RSC for EV batteries process map was built using the following considerations:

- The future process map considers that the companies have a partnership to provide a complete end-of-life management solution to one Electric vehicle manufacturer. Currently, the companies in this case study work independently and do not have any partnership in place. Remanufacturing_A, Repurposing_A and Recycler_A are running independent pilot projects with EV manufacturers to evaluate the feasibility of remanufacturing, repurposing, and recycling EoL EV batteries. However, in the interviews the participants mentioned their intentions to collaborate with other key players of the EoL RSC for EV batteries to make the most out of the capabilities of each of them and offer a full end-of-life management service to EV manufacturers. The interviewed companies recognise that building long-term business relationships between remanufacturers, material recyclers, and scrap car recyclers is necessary to succeed. These companies need each other to secure batteries and components supply. At the moment of the interview, the manager of Recycler_A said "*We already started discussions with other companies involved in the electric vehicle batteries EoL industry to build partnerships".*
- The EV batteries are collected through Dealer service centres and ATFs across the UK as it is currently done in the industry. As it was not possible to collect data from Dealer service centres, it was assumed that they follow the same processes as the ATF. For the purpose of the research and to simplify the sequences of activities of the model, all the activities that take place in the ATF and Dealer service centre are grouped as "Battery removal"
- The future map considers a centralised Testing Facility where the activities of batteries discharge, diagnosis, EoL route selection and initial disassembly takes place. The decision to include a centralised Testing facility was based on the process map analysis and interview findings. As it can be identified in the process map of the Remanufacturing_A (Figure 8.6), Repurposer_A (Figure Y), Recycler_A (Figure Z), the activities of discharge and diagnosis/testing repeat for all of them. According to the case study findings, these activities are considered

the most time consuming and complex for the interviewees. Recycler_A suggested, *"one of the most time-consuming parts of dismantling battery packs is getting around things like adhesives because operators have to be very careful when dismantling batteries and modules; otherwise, the product may get damaged".* Remanufacturer_A said, *"the diagnosis of the state of health of the batteries is a complex process"… "to measure the SOH of the battery is necessary to have either a reference from a new battery to benchmark against or have information about how exactly the battery was meant to perform. It's not one test that can be applied to every battery. This process requires developing multiple tests that need to be designed to be flexible enough to check batteries from different manufacturers and EV models".*

- The decision about what EoL route to follow (remanufacturing, repurposing, or recycling) is decided at the centralised testing facility. The operators at the testing facility decide the route depending on the SOH of the battery and components prioritising in the first place remanufacturing, second place repurposing and in the third place recycling as suggested by previous literature on end-of-life electric cars management (DeRousseau *et al.*, 2017) and circular economy strategies (Potting *et al.*, 2017).
- The study findings suggest that the activities involved in the end-of-life management of batteries such as remanufacturing, repurposing, and material recycling require unique expertise and technology. The study participants suggested that they do not intend to specialise on doing additional activities besides their core business. For this reason, each company in the model namely Remanufacturer, Repurposer and Recycler continue doing their core activities. The Testing Facility of the model provides Remanufacturer with the EV batteries and components to do their remanufacturing work. While, Repurposer receives from the Testing facility only the EV battery cells that can be used to build up new 2nd life batteries. Finally, Recycler receives the EV battery cells ready to split up in their recycling plant.

Figure 8.7 shows a simplified map that includes the activities performed by the supply chain actors of an integrated sustainable end-of-life RSC network for electric vehicle batteries. The process map presented in Figure 8.7. is the final process map built after the facilitated discussions with industry experts explained in section **8.6. Facilitated modelling intervention**. The process map does not include any disruption in the activities such as breaks or any other occasional stops that will not be considered in the process to be analysed. The main processes that have been mapped and included at the UK EoL supply chain for electric vehicle batteries of this study are the following:

a. Firstly, the batteries are collected from the market. The batteries that are still under the warranty period are collected through the dealer service centres, while the batteries that have exceeded the warranty period are collected through the ATFs.
b. After the batteries are removed from the EVs, these are sent to Testing Facility where the battery pack pass through an initial testing.
c. Then, the batteries are disassembled to module level, and send tested to decide the EoL route.
d. The modules in good conditions are sent to the remanufacturing plant for remanufacturing. After the remanufacturing process is completed the new batteries are tested and packed.
e. The modules that did not pass the module testing are disassembled to cell level.
f. The battery cells pass then pass through a grading to measure its performance.
g. The cells in good conditions that can be used to build up new second-life batteries are sent to the Repurposing plant. Once in the repurposing plant, the second life batteries are assembled, tested and packed.
h. The cells that did not pass the grading are sent to Recycling plant that receives the EV battery cells are scraped and the valuable material recovered.

This process map represents the sequence of steps in the process to be analysed (Figure 8.7).

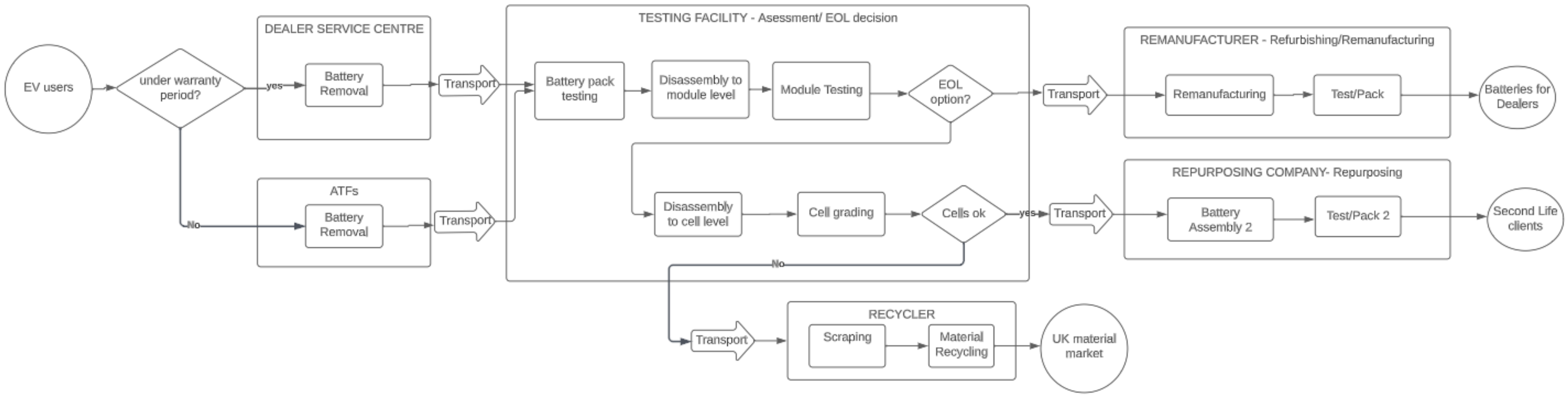


Figure 8.7. EoL EV batteries process map

8.3.3. Model content (Scope and level of detail)

Table 8.1. shows the proposed scope of the EV battery RSC model with a justification of what is being included in the model. The components are listed by type entity, activity, queue and resource.

Table 8.1. Summary of model scope (Author, 2024)

Component	Include/Exclude	Justification
Entities:		
Returned EV batteries	Include	Flow through the system
Activities:		
Collection from customers	Exclude	Assumption: the clients return the used batteries to the company garages and ATFs
Battery removal 1, Battery removal 2, Discharge, Diagnosis, Remanufacturing, Test/Pack 1, Disassembly to module level/testing, Disassembly for harvesting, disassembly to cell level/grading, battery assembly 2, Test/pack 2, scraping, material recycling	Include	Experimental factor; required to measure capacity, utilisation, sustainability metrics.
Queue:		
For every activity	Include	Required for waiting time, queue size response
Resources:		
Staff at Dealer service Centre, staff at ATF, staff at Test facility, staff at remanufacturing company, staff at repurposing company, staff at recycler.	Include	Required to perform the activities

Table 8.2 provides information about the level of detail covered by the components included in the scope of the EV battery RSC model.

Table 8.2. Summary of model detail (Author, 2024)

Component	Detail	Include/Exclude	Justification
Entities:			
Returned EV batteries	Quantity	**(Included/Exclude)**	One entity represents **(one/X)** returned EV battery
	Arrival pattern: forecast of battery returns	Include	Batteries flow through the system. **Forecast based on secondary data.**
	Attribute: Type of EV battery	Exclude	<u>Simplification</u>: Only considers lithium-ion battery.
Activities:			
Battery removal 1, Battery removal 2, Discharge, Diagnosis, Remanufacturing, Test/Pack 1, Disassembly to module level/testing, Disassembly for harvesting, disassembly to cell level/grading, battery assembly 2, Test/pack 2, scraping, material recycling	Quantity: number of stations for evaluation	Include	Affects process capacity
	Nature (X in Y out)		<u>Simplification</u>: Considers 1 in 1 out
	Cycle time: service time distribution	Include	Affects process capacity. Approximation to triangular distribution
	Breakdown: of tools and equipment	Exclude	<u>Assumptions</u>: Assume no breakdowns
	Resources	Include	Staff required to the activities
	Other: rework	Exclude	Simplification: not considered because it rarely happens
Queue:			
For every activity	Quantity: 1	Include	Single queue for each activity
	Capacity	**Exclude**	**Assumes no space limitation**
	Queue discipline: First in First out	Include	Affects time in the system
	Routing: to next activity	Include	Batteries flow to the next process

Component	Detail	Include/Exclude	Justification	
Resources:				
Staff at Dealer service Centre, staff at ATF, staff at Test facility, staff at remanufacturing company, staff at repurposing company, staff at recycler.	Quantity	Include	Experimental factor	
	Shifts	Exclude	<u>Assumption:</u> The process is measured by the working day. Difference between shifts is not relevant	
	Skill level	Exclude	<u>Assumption:</u> All the staff are of equal skill level	
	Other activities	Exclude	<u>Assumption:</u> Any other activity different from the classification of batteries is not considered	

8.4. Modelling input data

Interarrival time

The interarrival time has been estimated based on secondary data. The data considered is vehicle registered in the UK (Department for Transport, 2022) market share of a EV manufacturer (Department for Transport, 2022), 8-10 years estimated lifetime of EV battery (Gruber *et al.*, 2011). The number of EoL batteries forecasted per year may be found in Figure 8.8. A summary of historical records and forecast may be found in Appendix III – Forecast OEM EoL Batteries. Due to the software limitations, each battery in the system represents 8 batteries. The processing times have been adapted accordingly.

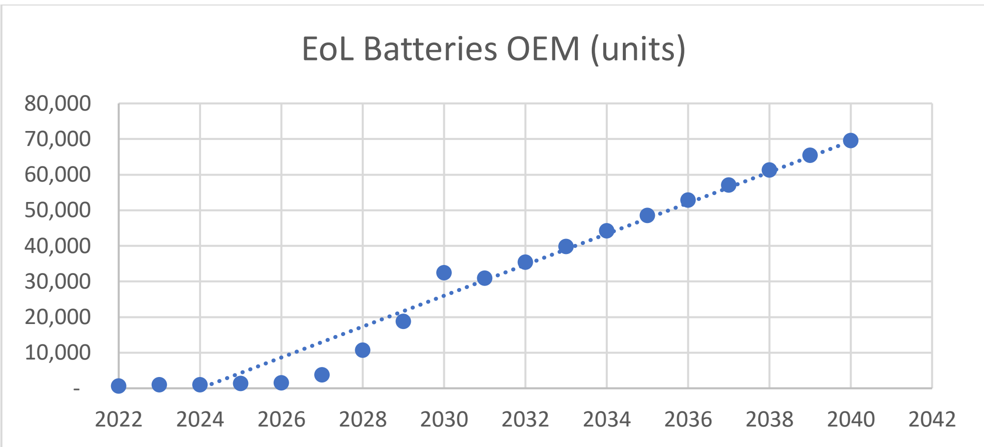


Figure 8.8. Forecast returned EoL Batteries (Author,2024)

Processing time (service time)

The processing times were estimated in based of the information provided by the participant ScrapCarRecycler_A, Remanufacturer_A, Repurposer_A, Recycler_A in the questionnaires and Client_AC, Client_RG, Client_EC, Client_CF , Client_CF2 in the facilitated modelling sessions. The service times of the processes were modelled using a triangular distribution as suggested by the literature in cases with limited historical data (Greasley, 2023). Triangular distribution has been applied before in supply chain modelling and allows industry practitioners to have more clarity about the critical inputs necessary for the analysis without being time consuming (Petrovic, Roy and Petrovic, 1998). A summary of the processing times used in the simulation model may be found in Table 8.3.

Table 8.3. Processing times EoL RSC for EV bateries (Author,2024)

Facility	Activity	Processing time (minutes)	Notes
Dealer service centre	Battery removal Dealer	Triangular (100,120,130)	Assuming same time as ATF. No access to data from Dealer Service centres
ATF	Battery removal ATF	Triangular (100,120,130)	Info provided by ScrapCarRecycling_A, Validated Client_RG
Testing facility	Testing whole battery pack	30	Info provided by Client_RG
Testing facility	Disassembly to module level	Triangular (20,120,210)	Info provided by Remanufacturer_A, Validated Client_EC
Testing facility	Testing module	30	Info provided by Remanufacturer_A, Validated Client_EC
Testing facility	Disassembly to cell level	Triangular (10,40,90)	Info provided by Remanufacturer_A,Validated Client_EC, Client_CF, Client_CF2
Testing facility	Grading cells	66	Info provided by Repurposer_A
Remanufacturing company	Remanufacturing	Triangular (260,300,360)	Info provided by Remanufacturer_A, Validated Client_EC
Remanufacturing company	Test/Pack 1	30	Info provided by Remanufacturer_A, Validated Client_RG
Repurposing company	Battery Assembly 2	Triangular (54,60,66)	Info provided by Repurposer_A
Repurposing company	Test/Pack 2	123	Info provided by Remanufacturer_A, Validated Client_RG
Recycling company	Scraping	Triangular (25,30,35)	Info provided by Recycler_A. Validated Client_RG, Validated Client_CF, Client_CF2
Recycling company	Material recycling	58	Info provided by Recycler_A.

8.4. Assumptions

This model considers the following assumptions.

- The type of battery consider for the simulation was Lithium-ion and chemistry NMC622.
- The entities that flow through the system are EV batteries. In the case of entities that use as a unit of analysis modules, cells or tons of material, these have been transformed to a battery equivalent to simplify the analysis.

- The model considers initially one dealer service centre, one ATF, one test facility, one remanufacturing company, one repurposing company and one material recycler. Each of them has a specific number of multitasking resources (operators) that can help with any process at their facilities. The analysis of the simulation results will suggest the estimated capacity requirements of the system.
- The lorries that transport batteries between facilities wait to have full-loaded shipments (8 batteries) to collect the batteries.
- The transportation time between facilities is 240 minutes and does not include loading and unloading time.
- The model considers that each of the companies works one shift, seven days a week.

8.5. Building the model

Having finished with the initial data collection, analysis and process mapping the simulation model that represents a UK EoL RSC for EV batteries was built. The discrete-event simulation model of the EoL RSC for EV batteries was built using the Arena Simulation Software v16.2 (Rockwell Automation, 2023). Arena Simulation software is a leading software in Discrete-event simulation used by most Fortune 100 companies and business school students (Rockwell Automation, 2023). Moreover, Arena allows modelling using an intuitive flowchart methodology that does not require complex programming skills.

The software allowed a simplified RSC network to be built following the process map in Figure 8.9 and Figure 8.10. Moreover, the model considers the returned EV batteries as entities and as activities, queues, and resources, as described in section 8.5.2.

The main blocks used were the "Create" block for the arrivals, the "Process" block for all the activities in the system (e.g. battery removal – dealer, battery pack testing, disassembly to cell level, etc) , "Decision" block for each of the decision points (e.g. under warranty period?, battery pack ok?, EoL option?, etc), the "Batch" block to accumulate the batteries until there are enough batteries for a full-load trip and "Dispose Block" at the end of the system. Figure 8.9 shows the collection section of the simulation model done at the Dealer Service centre and ATF. While Figure 8.10. shows the activities that take place at the Testing facility, Remanufacturing company, Repurposing company and recycler. The complete model can be found in Appendix V – Complete Simulation model.

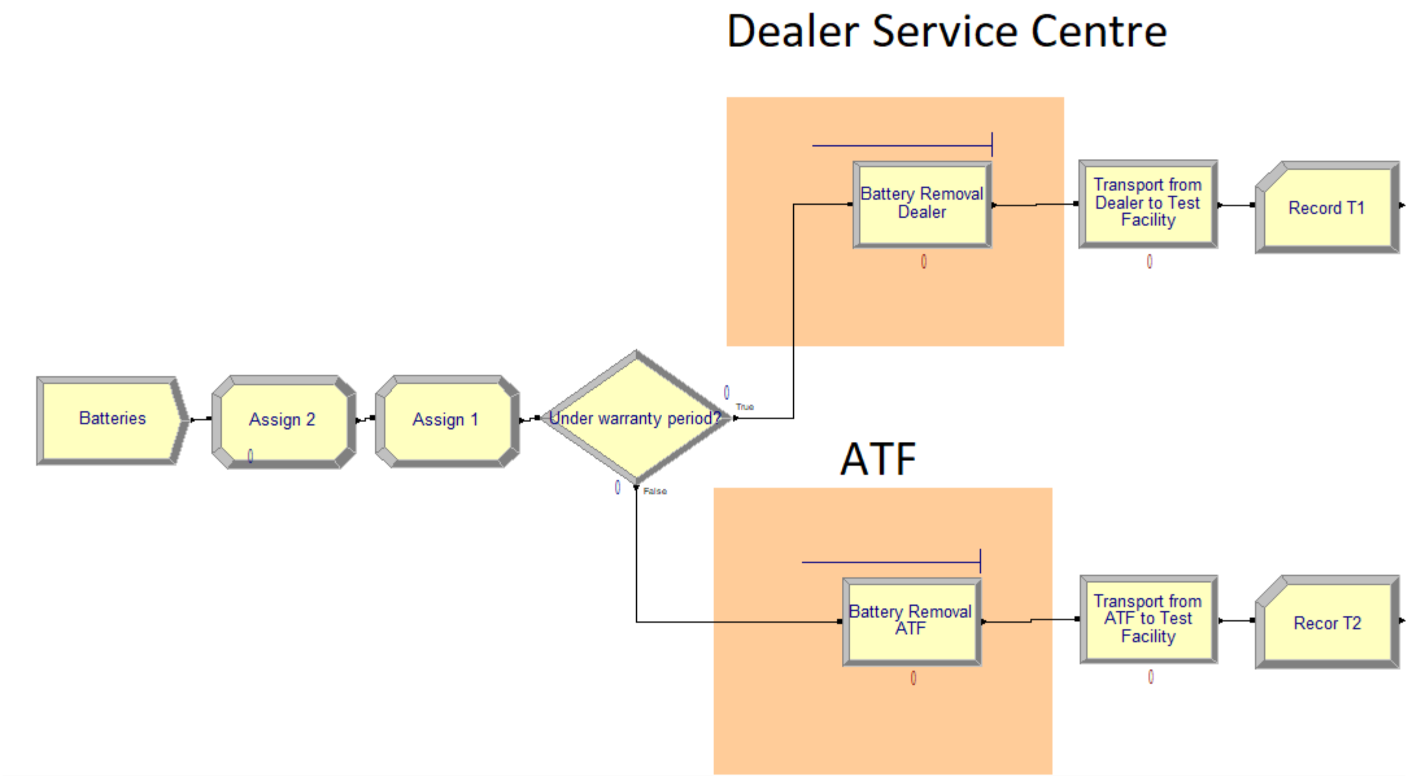


Figure 8.9. Simulation model part A (Collection process)

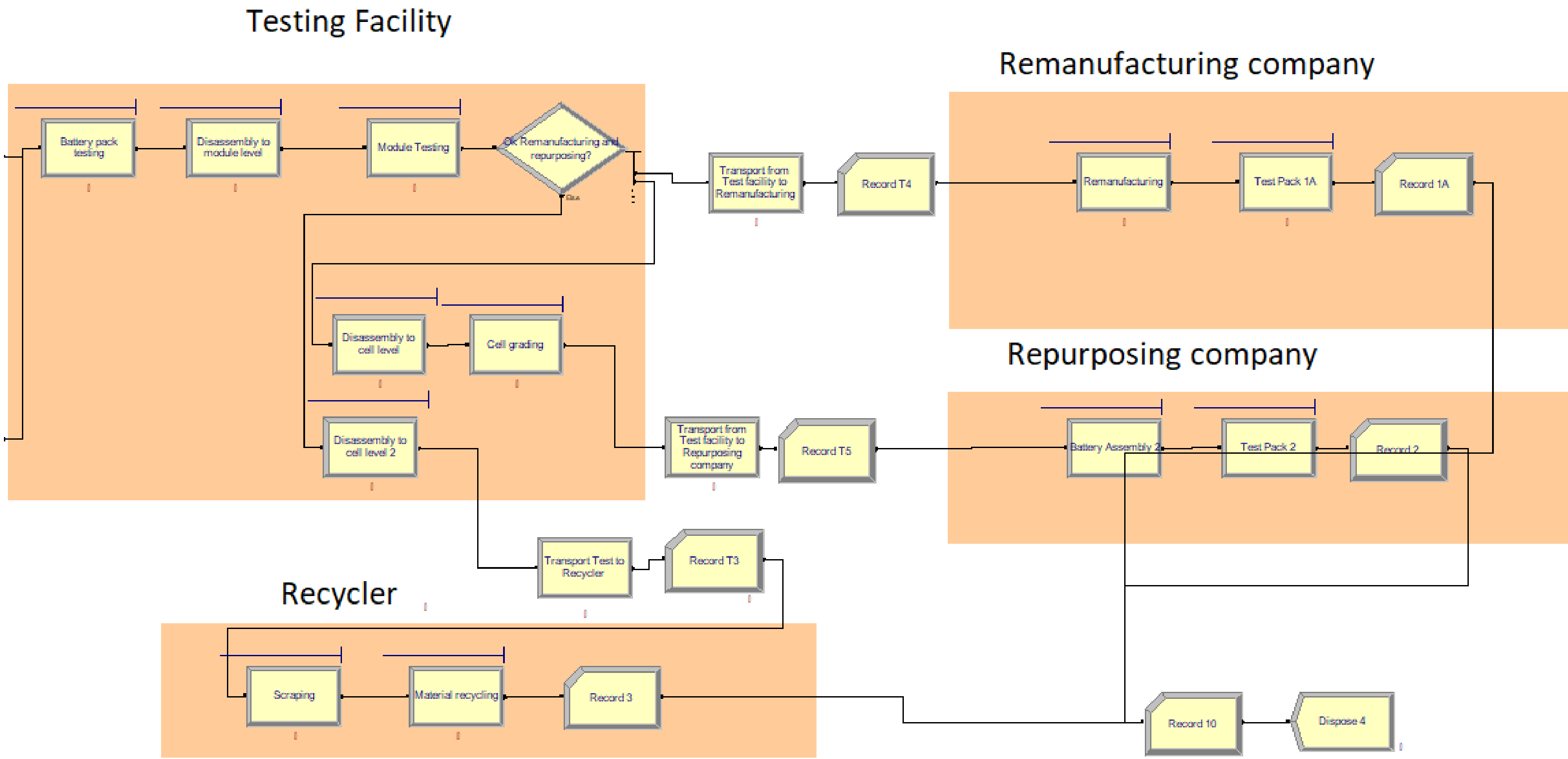


Figure 8.10. Simulation model part B (Process at Testing facility, Remanufacturer company, Repurposing company and recycling company)

8.6. Facilitated modelling intervention

Facilitated modelling is a process used by a facilitator to create models jointly with a group of people from an organization (Eden and Radford, 1990). The facilitating modelling techniques has been successfully used by several researchers (Robinson, 2001; Adamides and Karacapilidis, 2006; Den Hengst, De Vreede and Maghnouji, 2007; Tako, Kotiadis and Vasilakis, 2010). The research findings of previous facilitated modelling research suggest that the technique has proved to be useful to investigate and analyse complex problems at a strategic level. Moreover, the facilitated modelling technique has proved to be successful specially in cases where there is a lack of historical or appropriate data to do an objective analysis using simulation. Due to the lack of historical data and limited information of the established process to develop the process map of the RSC for EV batteries facilitated modelling intervention was conducted.

8.6.1. The context

The purpose of the facilitated modelling intervention conducted in this research was to complement the initial data collected through questionnaires and semi-structured interviews to managers and directors from **OEM_A, ScrapCarRecycling_A**, **Remanufacturer_A**, **Repurposing_A**, **Recycler_A**. It was identified that there was a lack of historical data to model the behaviour of the processing times, define process sequences. Moreover, there was more data needed to abstract an integrated and collaboratively EoL RSC for EV batteries that does not exist. Therefore the insight from participants with knowledge of the end to end process was needed. The participants of the facilitated modelling interventions were chosen due to their wide knowledge about the different EoL processes and experience working on EoL EV batteries projects and pilots. Moreover, the participants were identified as potential users of the proposed simulation model.

The participants of the facilitated interventions were:

- Client_AC: Environmental Planning Manager – Automotive company
- Client_RG: Technology and Innovation Manager – Recycling group
- Client_EC: Company Director – Engineering company
- Client_CF: Head of Forecasting – Consultancy Firm specialised in lithium-ion battery and electric vehicle supply chain.
- Client_CF2: Battery specialist and Senior Engineer from Circular Economy team – Consultancy Firm specialised in circular economy projects.

8.6.2. The facilitated modelling sessions

This description below outlines the sequence and nature of the activities performed for conducting the facilitated modelling sessions.

a. Participants were explained about the facilitated session objectives.
b. Participants were shown the initial proposed process map for the UK EoL RSC for EV batteries using Miro platform (Appendix IV- Process map Facilitated modelling session). Feedback from the participant was requested and main changes (process blocks and flows) were made in the live Miro document.
c. Due to the lack of historical data for the processing times, participants were asked for their expert opinion to validate and estimate the processing times. The service times of the processes were modelled using a triangular distribution as suggested by the literature in cases with limited historical data (Greasley, 2023). The participants were asked about the minimum, mode, maximum value for each of the processing times to fit it to a triangular distribution.
d. The initial simulation model built in Arena was shown. Participants were explained about the process blocks, routes, decision points used and resources. More details of the feedback about the simulation model are detailed in the 8.7.2. Validation – Conceptual validity and Believability. The initial simulation model was run and the initial key metrics were shown. Feedback was asked around the initial metrics calculated (i.e. processing time, number of batteries processes, resources, utilisation of resources). The suggestions around environmental and economic metrics were gathered and if considered relevant implemented in the simulation model. The full list of metrics recommended in the facilitated sessions and its implementation status is summarised in the Table 8.4.

Table 8.4. Metrics implementation status

Metric	Participant	Implemented in simulation model?	Data source of ratios
Number of remanufactured batteries	Client_AC	Yes	Remanufacturer_A
Number of repurposed batteries	Client_AC	Yes	Repurposer_A
Kg of total material recovered	Client_AC, Client_CF2	Yes	Recycler_A, Client_RG
Kg of raw material recovered (e.g. cobalt, lithium, nickel) and value in GBP £	Client_CF, Client_CF2	Yes	Recycler_A, WMG(2020)
Capacity - machines and human resources	Client_EC	Yes	N.A

Carbon impact of transport	Client_RG	No. No access to data	N.A
CO_2 emissions reduction	Client_RG, Client_CF2	Yes	(Crawford, Shao-Horn and Keith, 2022) (Yu, Bai and Ma, 2021) (Chen *et al.*, 2022)
Processing cost	Client_EC, Client_RG	No. No access to data	N.A.
Savings due to remanufacturing, repurposing and recycling	Client_CF2	Yes	(ICCT, 2018) (Engel, Hertzke and Siccardo, 2019)

8.7. Verification and Validation

The verification and validation were conducted to ensure that the model created provides a close representation of the system under study. As Sargent (2013) suggested, there is no fixed set of tests that can be applied to every DES model. Hence, for this research a group of verification and validation techniques steps were selected according to characteristics of the study. The methods for verification and validation of the UK EoL RSC for EV batteries model are discussed and justified below.

8.7.1. Verification

The aim of the verification process is to ensure that the simulation model built using the software is a correct representation of the process map of the system being studied (Greasley, 2023). For this research, the following verification techniques were used:

Structured walkthrough

The structured walkthrough procedure allows the modeller to include the perspective of people not involved directly with the modelling task. The walkthrough involves explaining to an individual or a group of people the computer model code and sequence and discussing the reasoning of the steps followed to identify errors (Greasley, 2023). The structured walkthroughs were conducted with researchers and academics of Aston Business School and the School of Engineering and Applied Science familiar with Arena Simulation Software. Some of the process blocks and sequence were reorganised according to the feedback received.

Animation inspection

The animation feature of Arena Simulation software is a useful tool that facilitates the understanding of the model behaviour. The animation allows looking simultaneously the model components and the behaviour of the entities (Greasley, 2023). The animation was conducted by adding images to the entities (EV batteries) and watching the life story of the entities by running the animated model in slow speed to check the logic of the model. The animation inspection technique was useful to identify if the entities were following the correct sequences or if there was any unexpected queue. In addition some headings and colours were added to the model for a better understanding of where each of the activities take place.

8.7.2. Validation

The validation process is used to assure that the model behaves close enough to the real system under examination (Greasley, 2023). In this case study as the simulation model is representing a potential EoL RSC that does not exist, the validation was supported using the facilitated modelling intervention sessions (Robinson *et al.*, 2014) with industry experts detailed in **8.6. Facilitated modelling intervention.**

The three aspects of validation proposed by Pegden, Shannon and Sadowski (1995) and Greasley (2023) are used: conceptual validity, believability and operational validity.

Conceptual validity (facilitated modelling intervention)

Conceptual validity ensures that the model built represents a credible approximation to the real-world system. To confirm the conceptual validity of this simulation model and increase its credibility, facilitated sessions were conducted with potential users of the simulation model. Individual facilitated sessions were arranged with potential users of the simulation model (Client_AC, Client_RG, Client_EC, Client_CF, Client_CF2) for the validation stage. In these meetings the conceptual model, simplification and assumptions of the EoL RSC for EV batteries of this study were shared with the participants. Some of the key elements of the conceptual model were explained and discussed. The participants shared new insights about the current situation of the EoL RSC of EV batteries in UK and mainland Europe.

Client_AC, Client_RG. Client_EC, Client_CF and Client_CF2 made some observations suggesting changes in the activities shown in the process map. Some of these recommendations were taken while others were dismissed due to the model objectives. For instance, the activity "Battery pack testing" was added to the process map since Client_RG suggested that new technology has been developed that allow testing before battery pack disassembling. Client_EC suggested that nowadays ATFs are disassembling batteries to do a preliminary health check of the battery. That suggestion was not considered to avoid the duplication of testing activities in the model. Client_RG agreed that even though the disassembling in an ATF and Recyclers is a common practice is not the most efficient one, and it would be better to leave that activity to technical experts in a specialised testing facility. An additional Dismantling to cell block added to the model based on Client CG and Client CF2 feedback. According to on Client

CG and Client CF2, the process of dismantling to cell level for repurposing is different from the dismantling for recycling because the dismantling for recycling can be destructive and as a consequence take less time.

Believability (facilitated modelling intervention)

The third aspect of validation is believability. The believability consists of ensuring that the module outputs are credible for the simulation users (Greasley, 2023). This part of the validation was conducted as well with the potential industry users of the simulation model. To ensure believability, individual interviews were arranged with managers and directors from a car manufacturer and companies involved on the EoL management of EV batteries. The simulation project objectives, the capabilities of the simulation model and assumptions were explained to the participants. To support the explanation and further discussion of the simulation model the structured walkthrough and animation inspection were used. For the structured walkthrough the Arena model flowchart was shown to the participants to ensure that the model was a close representation of a potential EoL RSC for EV batteries. The animation of the simulation model running in slow speed was also shared live with the industry experts to ask for their feedback. The animation also included some performance metrics such as Labour Cost, utilisation of resources (See Figure 8.10). Client_AC, Client_RG, Client_EC, Client_CF and Client_CF2 validated that the metrics Labour cost, and capacity of the system were relevant metrics to assess the performance of the model proposed. Client_EC suggested that for its company future projects they are planning to have different companies operating under the same roof doing the disassemble, SOH assessment, remanufacturing, repurposing, recycling. Client_CF also suggested to choose an specific battery chemistry to make a more detailed estimation of the specific raw material recovered through recycling.

In addition, some changes were made in the processing times and the number of resources for bottleneck processes during the interviews to show in a visual way how the queues and performance metrics changed accordingly. Some processing times were validated while others updated according to the feedback and justifications of Client_AC, Client_EC, Client_RG, Client_CF.

Showing the animation of the simulation model also helped to get insights about new performance metrics that the industry experts were interested in knowing from the simulation model.

The suggestions from the participants for performance metrics were the following:

- Number of remanufactured batteries (Client_AC) **(Implemented)**

- Number of repurposed batteries (Client_AC) **(Implemented)**
- Kg of total material recovered (Client_AC, Client_CF2) **(Implemented)**
- Kg of raw material recovered (e.g. cobalt, lithium, nickel) and value in GBP £ (Client_CF, Client_CF2) **(Implemented)**
- Capacity - machines and human resources (Client_EC) **(Implemented)**
- The carbon impact of transport (Client_RG)
- CO_2 emissions reduction (Client_RG, Client_CF2) **(Implemented)**
- Processing cost (Client_EC, Client_RG)
- Savings due to remanufacturing, repurposing and recycling (Client_CF2) **(Implemented)**

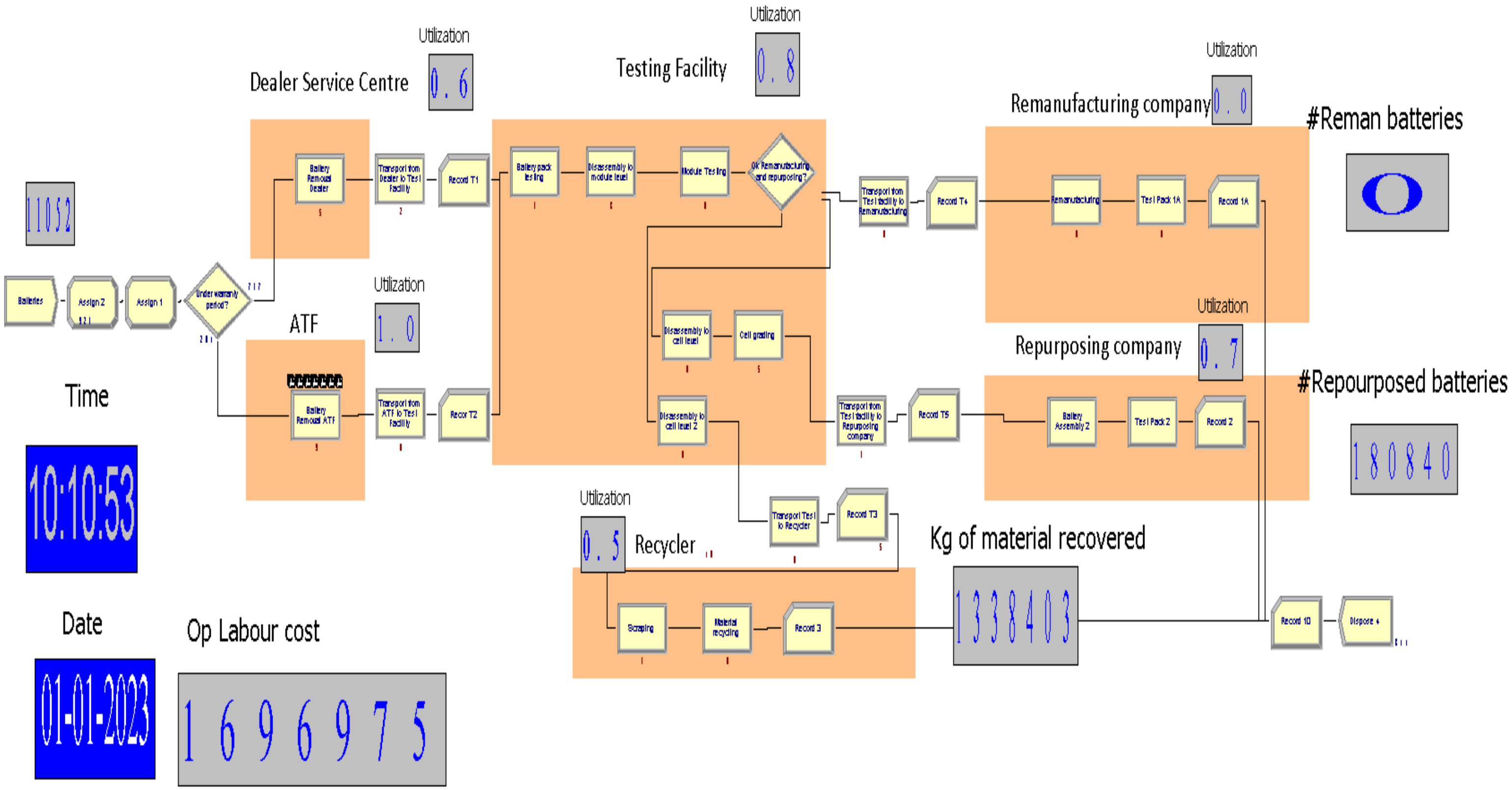


Figure 8.11. Animation Simulation model

Operational validity - Sensitivity analysis

The operational validity can be usually confirmed by comparing the results obtained in the model with the real-world performance (Greasley, 2004). In this case study, as the simulation model represents a potential EoL RSC that does not exist, the validation was conducted by conducting a sensitivity analysis of the simulation model subsystems. Banks *et al.* (2005) suggest some alternatives to validate the DES model behaviour for systems with no operational or limited historical data. The alternatives suggested by Banks *et al.* (2005) are parameter sensitivity test and structural sensitivity test.

For this study, the operational validity was confirmed by performing a sensitivity analysis of the process durations and adapting chance decision points. The sensitivity analysis was conducted to identify if the built simulation model behaves as expected and ensure that the input data used and model representation are appropriate for the study needs.

The sensitivity analysis of the process durations was conducted using the program Process Analyser[22] that is a complementary program of Arena Simulation Software.

For each of the processing times a low level and high level were defined (See Table 8.5). For each of the factors a variation of 20% in the processing time was considered.

[22] Process Analyser, you can adjust input parameters (variables, resource capacities, replication parameters) and define response variables (COUNTERS, DSTATS (time-persistent statistics), TALLY (tally-based statistics), OUTPUT statistics) for a simulation model.

Table 8.5. Factors for sensitivity analysis (Author, 2024)

Factor	Description	Base level		Change	Low level	High level
A	Battery Removal - Dealer	PT_BRd =	triangular(100,120,130)*batchsize	(+/-)20%	PT_BRd*0.8	PT_BRd*1.2
B	Battery Removal - ATF	PT_BRa =	triangular(100,120,130)*batchsize	(+/-)20%	PT_BRa*0.8	PT_BRa*1.2
C	Battery Pack testing	PT_BPT =	30*batchsize	(+/-)20%	PT_BPT*0.8	PT_BPT*1.2
D	Disassembly to module level	PT_DML =	triangular(20,120,210)*batchsize	(+/-)20%	PT_DML*0.8	PT_DML*1.2
E	Module Testing	PT_MT =	30*batchsize	(+/-)20%	PT_MT*0.8	PT_MT*1.2
F	Disassembly to cell level	PT_DCL =	triangular(10,40,90)*batchsize	(+/-)20%	PT_DCL*0.8	PT_DCL*1.2
G	Cells grading	PT_CG =	160*batchsize	(+/-)20%	PT_CG*0.8	PT_CG*1.2
H	Remanufacturing	PT_R=	triangular(260,300,360)*batchsize	(+/-)20%	PT_R*0.8	PT_R*1.2
I	Test Pack 1	PT_TP1 =	30*batchsize	(+/-)20%	PT_TP1*0.8	PT_TP1*1.2
J	Battery Assembly	PT_BA =	60*55*batchsize	(+/-)20%	PT_BA*0.8	PT_BA*1.2
K	Test Pack 2	PT_TP2 =	495*batchsize	(+/-)20%	PT_TP2*0.8	PT_TP2*1.2
L	Scraping	PT_S =	triangular(25,30,35)*batchsize	(+/-)20%	PT_S*0.8	PT_S*1.2
M	Material Recycling	PT_MR =	58*batchsize	(+/-)20%	PT_MR*0.8	PT_MR*1.2

Scenarios were run for each of the factors. Table 8.6 shows the results of the sensitivity analysis of five factors (Factor A : Battery Removal - Dealer , Factor B : Battery Removal – ATF, Factor C : Battery Pack testing, Facto F : Disassembly to cell level, Factor K: Test Pack 2). For all the factors a variation of -20% of the processing time makes the entity total time reduce and a variation of +20% makes the Entity total time increase. However, it may be observed that the Entity total time is not particularly sensitive to the changes in the processing time of any of the factors.

Table 8.6. Sensitivity analysis results (Author, 2024)

Factor/Scenario	Level	Processing time	Entity total time	Variation Entity total time
Factor A : Battery Removal - Dealer				
Scenario 1	Low level	PT_BRd*0.8	771,102	-0.8%
Scenario 2	Base level	PT_BRd*1	777,646	0.0%
Scenario 3	High level	PT_BRd*1.2	843,152	+1.4%
Factor B : Battery Removal - ATF				
Scenario 4	Low level	PT_BRa*0.8	777,029	-0.1%
Scenario 5	Base level	PT_BRa*1	777,646	0.0%
Scenario 6	High level	PT_BRa*1.2	792,563	+1.9%
Factor C : Battery Pack testing				
Scenario 7	Low level	PT_BPT*0.8	772,323	-0.7%
Scenario 8	Base level	PT_BPT*1	777,646	0.0%
Scenario 9	High level	PT_BPT*1.2	792,115	+1.9%
Factor F : Disassembly to cell level				
Scenario 10	Low level	PT_DCL*0.8	772,571	-0.7%
Scenario 11	Base level	PT_DCL*1	777,646	0.0%
Scenario 12	High level	PT_DCL*1.2	777,739	+0.01%
Factor K : Test Pack 2				
Scenario 13	Low level	PT_TP2*0.8	772,524	-0.7%
Scenario 14	Base level	PT_TP2*1	777,646	0.0%
Scenario 15	High level	PT_TP2*1.2	782,978	+0.7%

8.9. Experimentation

8.9.1. Output analysis

In order to obtain reliable results from the simulation experimentation it is essential to identify the nature of the simulation system and output, deal with initial bias, obtain sufficient data and choose appropriate performance measures (Greasley, 2023). For this case study it was identified that the system is an non-terminating system since this model assumes a continues operation (24/7) commonly used in manufacturing companies (Greasley, 2023). As a non-terminating system, the simulation output is transient (i.e irregular) during the warm-up period. After the start period the simulation outcome becomes steady state.

8.9.1. Warm up period

The Arena Output analyser software application was used to calculate the warm-up period of the model, which is necessary to ensure that the simulation report data and performance measures are collected only after the simulation is in a steady state.The graph method was used to visually identify the discard point of the simulation output of a performance measure over a period. According to Figure 8.11 the steady-state behaviour is achieved after 35,000 minutes (warm-up period).

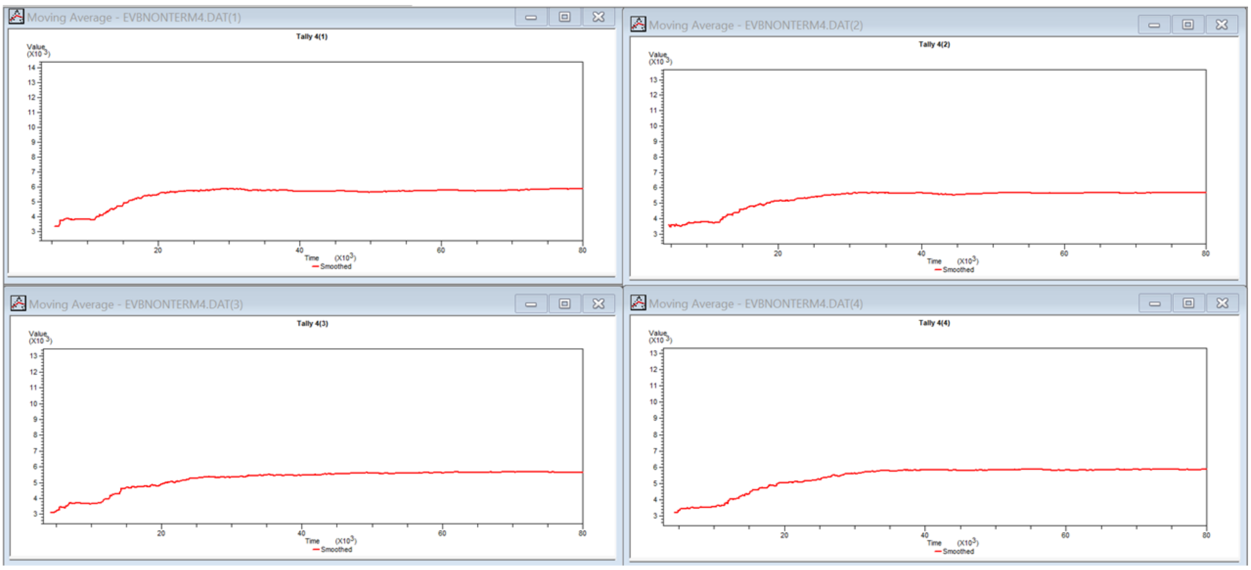


Figure 8.12. Average of EV batteries time in system (4 replications) (Author, 2024)

8.9.2. Results

The correspondent warm-up period (35,000 min) was added to the run setting of Arena to analyse the results the same way as a terminating system. The replication period was 350,000 min since it is recommended to have a replication period of at least 10 times the warm-up period (Greasley, 2023). Output analyser was used to estimate the confidence interval of the system. To increase the statistical precision of the performance measures 50 replications were run (Figure 8.12). According to the results, the estimated time of the batteries in the system is 98.4 hours with a half width[23] of 1.08 hours.

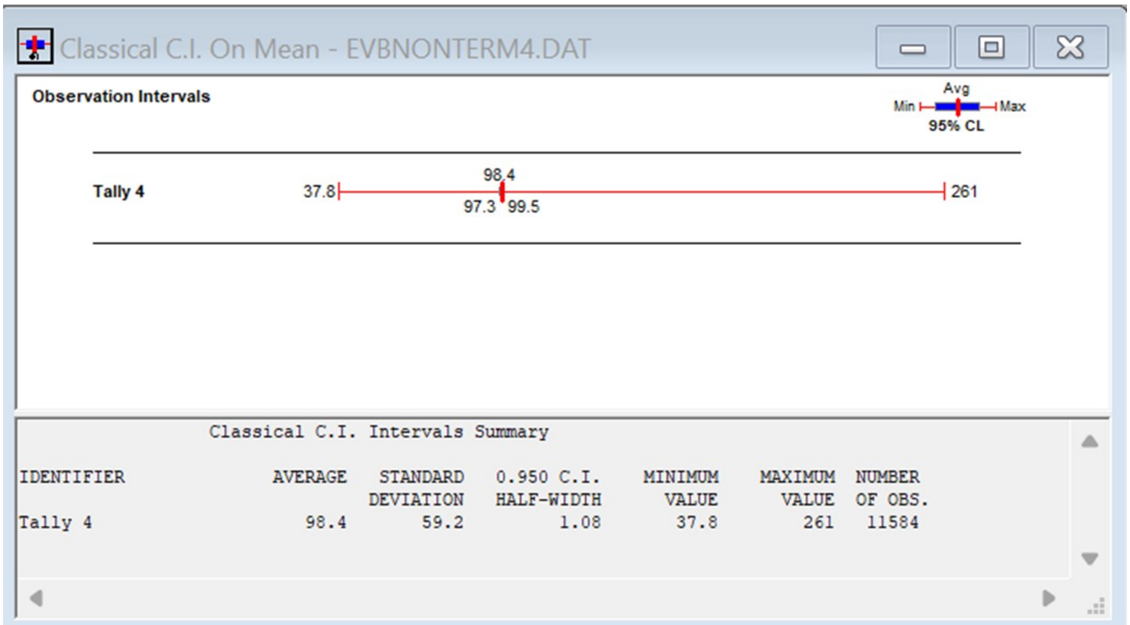


Figure 8.13. Output Analyser Confidence Interval EV batteries time in system

A set of experiments was used to test the versatility of the simulation model to represent different potential future scenarios in the EoL RSC of EV batteries model and assess their sustainability impact. Four themes were chosen to run the scenario experiments and explore the economic and environmental impact of changes in the EoL RSC of EV batteries.

The scenarios explored changes in:

- Processing times of activities (disassembling, testing),
- The proportion of batteries sent to recovery facilities (i.e. recycling, remanufacturing, repurposing)

[23] Half of the 95th percentile confidence interval for the metric

- Future demand levels according to the demand forecast in Appendix III – Forecast OEM EoL Batteries.

Baseline scenario

The baseline scenario considers that in 2035 the volume of batteries arriving in the system is 45,424 per year based in the EoL batteries forecast detailed in **Appendix III – Forecast OEM EoL Batteries.** Considering a constant interarrival time, the system receives 1 battery every 1.44 hours. This group of scenarios considers that 50% of the batteries are sent for recycling 25% for remanufacturing and 25% for repurposing.

Type A scenarios – Disassembling collaboration scenarios

According to the case study findings, the disassembling of batteries is currently done manually without following a standardised process due to battery design characteristics and lack of disassembling information. Therefore, the disassembling process is time-consuming and expensive due to the long labour hours assigned to this activity. The study participants agreed that the disassembling process was considered a key process that required improvement to reduce the throughput time of batteries in the system and set the capacity to meet future demand. For this reason, according to the case study participants the companies not specialised in dismantling of batteries and components are planning to collaborate with companies that have the disassembling capabilities.

This group of scenarios consider a variation in the disassembling time because of an improvement in the disassembling process as a consequence of a collaboration with EoL management companies specialised in disassembling.

For the Type A experiments, the disassembling processing time across the operations was reduced by 15% and 30%.

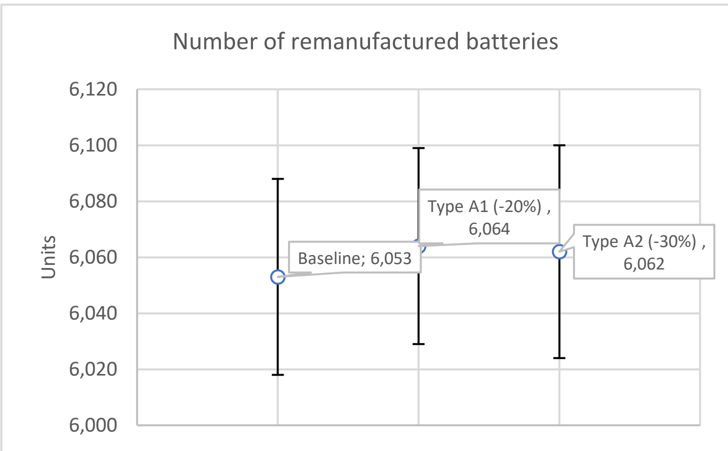
- **Baseline:** is the initial base scenario
- **Type A 1:** considers a reduction of 20% in the disassembly processing time
- **Type A 2:** considers a reduction of 30% in the disassembly processing time

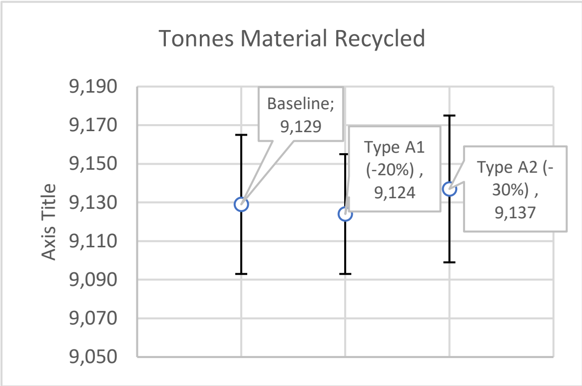
The resources were balanced for each scenario, considering a maximum of 80% of resource utilisation.

Table 8.7. Type A scenario conditions

		Type A - Disassembling		
		Baseline	**Type A1 (-15%)**	**Type A2 (-30%)**
Batteries arrival	Year	*2035*	*2035*	*2035*
	EoL Battery arrival per year	485,181	485,181	485,181
	Market share (10%)	48,518	48,518	48,518
	Interarrival time (hours)	1.44	1.44	1.44
	Entities arriving	1	1	1
EoL Route	Recycling	50%	50%	50%
	Remanufacturing	25%	25%	25%
	Repurposing	25%	25%	25%

The results suggest that reducing the disassembling time does not have a strong impact on Tonnes of material recycled, Number of remanufactured batteries and number of repurposed batteries (See Figure 8.13). When comparing the Tonnes of recycled material, Number of remanufactured batteries, and number of repurposed batteries of the **Baseline** vs. **Type A 1**, the results suggest no variation. Similar results are obtained when comparing **Baseline** scenario vs. **Type A 2**. However, the **Type A2** scenario allowed the reduction of 4 operators in the Dealer service centre and 4 operators in the Test facility (See Table 8.8).





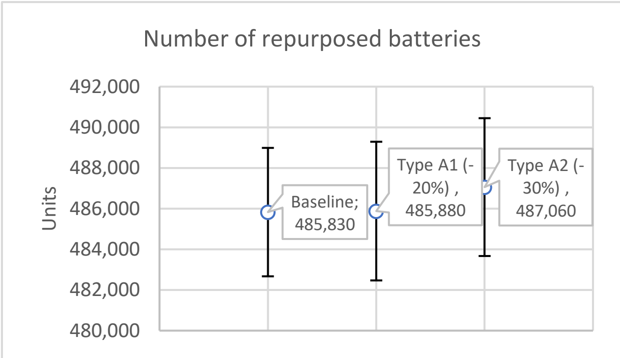


Figure 8.14. Scenarios Type A - Boxplots Tonnes of material recycled, Number of remanufactured batteries and repurposed batteries (Author, 2024)

Table 8.8 shows a summary of the staff headcount assigned to each facility and their correspondent utilisation for each scenario.

Table 8.8. Scenarios Type A - Staff and Staff utilisation (Author, 2024)

		Type A – Disassembling collaboration		
		Baseline	**Type A1 (-20%)**	**Type A2 (-30%)**
Staff	DealerCentreStaff	**12**	**9**	**8**
	ATFStaff	3	3	3
	TestFacilityStaff	**14**	**13**	**10**
	RemanufStaff	9	9	9
	RecyclerStaff	2	2	2
	RepurposingStaff	22	22	22
Staff Utilisation	RecyclerStaff.ScheduledUtilization	69%	54%	49%
	RepurposingStaff.ScheduledUtilization	79%	79%	79%
	TestFacilityStaff.ScheduledUtilization	77%	71%	76%
	RemanufStaff.ScheduledUtilization	79%	76%	79%
	ATFStaff.ScheduledUtilization	79%	58%	51%
	DealerCentreStaff.ScheduledUtilization	72%	77%	67%

Table 8.9 shows a summary of the economic and environmental impact of each of the Type A experiments.

Table 8.9. Scenarios Type A - Economic and environmental impact (Author, 2024)

	Baseline	**Type A1 (-20%)**	**Type A2 (-30%)**
Profit sales of recycled material (k£) (Average)	18,258	18,250	18,274
CO_2 **emission reduction (kg** CO_2**-eq) (Average)**	22,823	22,813	22,843
Savings due to remanufacturing (k£) (Average)	5,447	5,458	5,457
CO_2**-eq emission reduction (kg** CO_2**-eq) (Average)**	21,515	21,558	21,554
Savings due to repurposing (k£) (Average)	54,656	54,662	54,794
CO_2 **emission reduction (kg** CO_2**-eq) (Average)**	34,543	34,546	34,630

Type B scenarios –Testing collaboration scenarios

The case study findings suggest that testing time was another key activity that required improvement. Testing batteries, modules, and cells are activities with long processing times. As discussed with the study participants, they are already planning to address this issue and reduce the testing time through collaborations with other companies in the industry and research groups. This group of scenarios consider a variation in the testing time because of an improvement in the testing process, as mentioned in one of the sustainability strategies (SE4, SE5) identified in the case studies.

Similarly to the disassembling process, the testing time was considered another key process that required improvement to reduce the throughput time of batteries and set the capacity of the RSC to be able to meet future demand. For this reason, according to the case study participants companies like Remanufacturer_A, Repurposer_A are planning to collaborate with research institutions and consultancy firms to improve to testing process.

This group of scenarios consider a variation in the disassembling time because of an improvement in the testing process as a consequence of a collaboration with EoL management companies specialised in disassembling.

For the Type B experiments, the testing time of batteries, modules, and cells across the operations was reduced by 20% and 30%, respectively.

- **Baseline:** is the initial base scenario
- **Type B 1:** considers a reduction of 20% in the testing time
- **Type B 2:** considers a reduction of 30% in the testing time

Table 8.10. Type B scenario conditions

		Type B – Testing collaboration		
		Baseline	**Type B1 (-20%)**	**Type B2 (-30%)**
Batteries arrival	Year	*2035*	*2035*	*2035*
	EoL Battery arrival per year	485,181	485,181	485,181
	Market share (10%)	48,518	48,518	48,518
	Interarrival time (hours)	1.44	1.44	1.44
	Entities arriving	1	1	1
EoL Route	Recycling	50%	50%	50%
	Remanufacturing	25%	25%	25%
	Repurposing	25%	25%	25%

For each of the scenarios, the resources were balanced, considering a maximum of 80% of utilisation.

The results suggest that reducing the testing time has a slight positive impact on Tonnes of recycled material, the number of remanufactured and repurposed batteries (See Figure 10). The positive impact in Tons of material recycled, number of remanufactured batteries, and number of repurposed batteries could be obtained by maintaining the same staff headcount and testing machines. (See Figure 8.14).

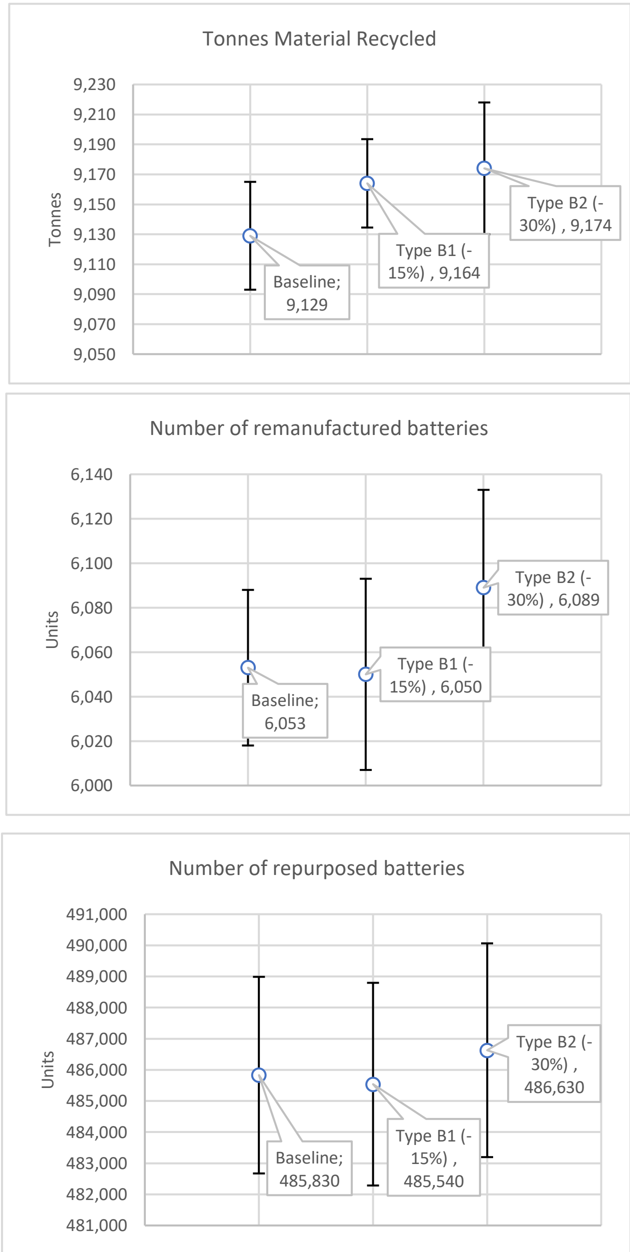


Figure 8.15. Scenarios Type B - Boxplots Tonnes of material recycled, Number of remanufactured batteries and repurposed batteries (Author, 2024)

Table 8.11. Scenarios Type B - Economic and environmental impact (Author, 2024)

	Baseline	Type B1 (-20%)	Type B2 (-30%)
Profit sales of recycled material (k£) (Average)	18,258	18,250	18,274
CO_2 emission reduction (kg CO_2-eq) (Average)	22,823	22,813	22,843
Savings due to remanufacturing (k£) (Average)	5,447	5,458	5,457
CO_2-eq emission reduction (kg CO_2-eq) (Average)	21,515	21,558	21,554
Savings due to repurposing (k£) (Average)	54,656	54,623	54,746
CO_2emission reduction (kg CO_2 eq) (Average)	34,543	34,522	34,599

Table 5. shows a summary of the staff headcount assigned to each facility and their correspondent utilisation for each scenario.

Table 10. Scenarios Type B - Staff and Staff utilisation

		Type B – Testing collaboration		
		Baseline	**Type B1 (-20%)**	**Type B 2(-30%)**
Staff	DealerCentreStaff	12	12	12
	ATFStaff	3	3	3
	TestFacilityStaff	15	14	14
	RemanufStaff	9	9	9
	RecyclerStaff	2	2	2
	RepurposingStaff	22	22	22
Staff Utilisation	RecyclerStaff.ScheduledUtilization	69%	70%	69%
	RepurposingStaff.ScheduledUtilization	79%	79%	79%
	TestFacilityStaff.ScheduledUtilization	77%	77%	77%
	RemanufStaff.ScheduledUtilization	79%	78%	79%
	ATFStaff.ScheduledUtilization	79%	72%	72%
	DealerCentreStaff.ScheduledUtilization	72%	72%	72%

Type C scenarios – Battery routing scenarios

This group of scenarios was built based on the discussions in the facilitated modelling sessions. When participants were asked about the potential routes that batteries would follow, they mentioned that the proportion of batteries sent for recycling, remanufacturing and repurposing will depend on several factors such as country legislations, battery technology/chemistry innovation and aftermarket. Participants Client_CF and Client_CF suggested to do experiments with extreme scenarios that consider a minimum of 50% recycling.

This group of scenarios consider a variation in the proportion of batteries routed for remanufacturing, repurposing and recycling.

- **Baseline:** it is the initial baseline scenario. This group of scenarios considers that 50% of the batteries are sent for recycling 25% for remanufacturing and 25% for repurposing.
- **Type C 1:** this scenario considers that all the batteries (100%) that enter the system go for recycling, which was achieved by sending collected batteries for disassembling to the cell level and then sending all of them for recycling.
- **Type C 2:** the second type C scenario considers that 50% of the batteries are sent for recycling and 50% for remanufacturing. This was achieved by sending 50% of the collected batteries for an initial disassembling and then sending them for recycling. The remaining 50% of the batteries were sent for initial disassembling, module testing, and remanufacturing.
- **Type C 3:** the last scenario considers that 50% of the batteries are sent for recycling and 50% for repurposing. In this scenario, 50% of the collected batteries were sent for initial disassembling and then for recycling. At the same time, the remaining 50% of the batteries were sent for disassembling, testing and repurposing.

Table 8.12. Type C scenario conditions (Author, 2024)

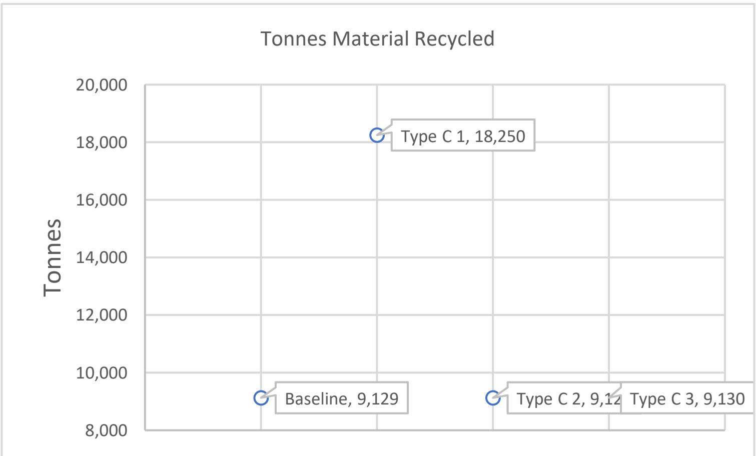
		Type C – Battery routing			
		Baseline	**Type C1**	**Type C2**	**Type C3**
Batteries arrival	Year	*2035*	*2035*	*2035*	*2035*
	EoL Battery arrival per year	485,181	485,181	485,181	485,181
	Market share (10%)	48,518	48,518	48,518	48,518
	Interarrival time (hours)	1.44	1.44	1.44	1.44
	Entities arriving	1	1	1	1
EoL Route	Recycling	50%	100%	50%	50%
	Remanufacturing	25%	-	50%	-
	Repurposing	25%	-	-	50%

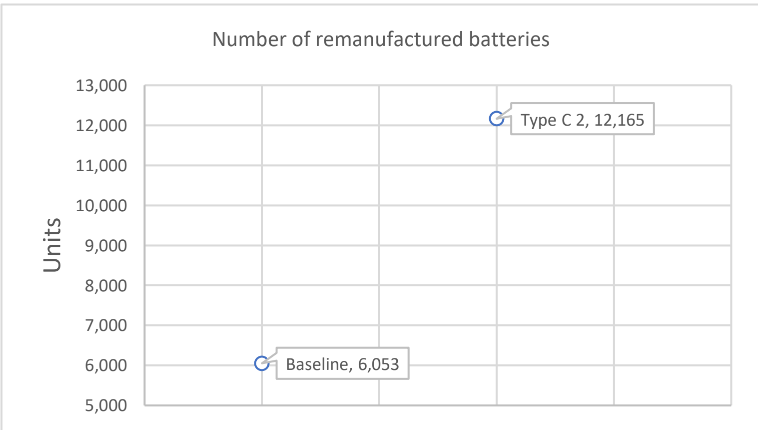
For each of the scenarios, the resources were balanced, considering a maximum of 80% of utilisation.

The results show the impact of selecting different EoL strategies. For instance, the results of Type C1 scenario that considers 100% of batteries going straight for recycling could get 18,250 tonnes of material recycled (See Figure 8.15) and a £36,500 k as an average profit sales of recycled material and an average reduction of 45,625 CO_2 emission. (kg CO_2-eq).

In Type C2 scenario, the tonnes of recycled material was reduced by 50%, and the number of recycling machines reduced from 7 to 4, adding 13 people to the remanufacturing process. The profits for recycled material and CO_2 emissions reductions went down by 50%; however, the 12,165 remanufactured batteries allowed savings of £10,949 k and a reduction of emissions of 43,247 (tonnes CO_2-eq).

In the case of scenario Type C3, sending 50% of the batteries for recycling and 50% for repurposing required the addition of 43 people to the repurposing process. This strategy allowed the production of 972,890 repurposed batteries that generated a £109,450k savings due to repurposing and a CO_2 emission reduction of 69,172 tonnes CO_2-eq.





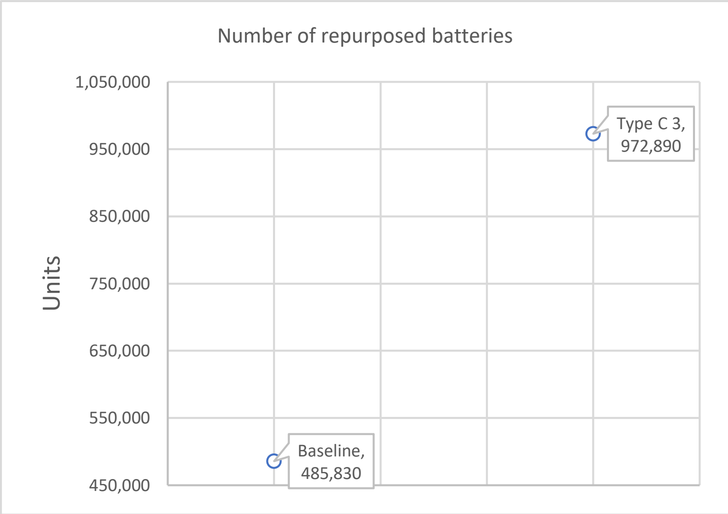


Figure 8.16. Scenarios Type C - Boxplots Tonnes of material recycled, Number of remanufactured batteries and repurposed batteries

Table 8.13 shows a summary of the economic and environmental impact of each of the Type A experiments.

Table 8.13. Scenarios Type C - Economic and environmental impact (Author, 2024)

	Baseline	Type C 1	Type C 2	Type C 3
Profit sales of recycled material (k£) (Average)	18,820	36,500	18,252	18,260
CO_2 **emission reduction (kg** CO_2**-eq) (Average)**	22,823	45,625	22,815	22,825
Savings due to remanufacturing (k£) (Average)	5,447	-	10,949	-
CO_2**-eq emission reduction (kg** CO_2**-eq) (Average)**	21,515	-	43,247	-
Savings due to repurposing (k£) (Average)	54,656	-	-	109,450
CO_2 **emission reduction (kg** CO_2**-eq) (Average)**	34,543	-	-	69,172

Table 8.14 shows a summary of the staff headcount assigned to each of the facilities and their correspondent utilisation for each of the scenarios.

Table 8.14. Scenarios Type C - Staff and Staff utilisation

		Type C - Routing			
		Baseline	**Type C1**	**Type C2**	**Type C3**
Staff	DealerCentreStaff	12	12	12	12
	ATFStaff	3	3	3	3
	TestFacilityStaff	15	15	15	15
	RemanufStaff	9	-	13	-

	RecyclerStaff	2	4	2	2
	RepurposingStaff	22	-	-	43
Staff Utilisation	RecyclerStaff.ScheduledUtilization	69%	69%	69%	69%
	RepurposingStaff.ScheduledUtilization	79%	-	-	80%
	TestFacilityStaff.ScheduledUtilization	77%	72%	72%	72%
	RemanufStaff.ScheduledUtilization	79%	-	79%	-
	ATFStaff.ScheduledUtilization	79%	72%	72%	72%
	DealerCentreStaff.ScheduledUtilization	72%	72%	72%	72%

Type D scenarios – Demand scenarios

Another key group of experiments built based on the findings of the facilitated modelling sessions was the volume scenarios. The study participants suggested that the volume scenarios of returned batteries are crucial to planning the capacity of RSC for EOL batteries and assessing future sustainability impact.

These scenarios consider a variation in the volume of batteries returned from the market based on the forecast detailed in Appendix III – Forecast OEM EoL Batteries.

- **Type D1 (2033):** The scenario considers that in 2033 the volume of batteries arriving in the system is 39,813 per year based in the EoL batteries forecast detailed in **Appendix III – Forecast OEM EoL Batteries.**
- **Baseline (2035):** The baseline scenario considers that in 2035 the volume of batteries arriving in the system is 45,424 per year based in the EoL batteries forecast detailed in **Appendix III – Forecast OEM EoL Batteries.**
- **Type D2 (2037):** The baseline scenario considers that in 2033 the volume of batteries arriving in the system is 57,065 per year based in the EoL batteries forecast detailed in **Appendix III – Forecast OEM EoL Batteries.**

Table 8.15. Type D scenario conditions

		Type D - Demand		
		Type D1 (2033)	Baseline (2035)	Type D2 (2037)
Batteries arrival	Year	*2033*	*2035*	*2037*
	EoL Battery arrival per year	398,126	485,181	570,651
	Market share (10%)	39,813	48,518	57,065
	Interarrival time (hours)	1.75	1.44	1.22
	Entities arriving	1	1	1
EoL Route	Recycling	50%	50%	50%
	Remanufacturing	25%	25%	25%
	Repurposing	25%	25%	25%

For each of the scenarios, the resources were balanced, considering a maximum of 80% of utilisation.

The results show the environmental impact of different demand levels. For instance, the results of Type D1 scenario show that for a demand level of 39,813 EoL batteries, 7,513 tonnes of material could be recycled (See Figure 8.16) which represents an average profit of £15,026k due to the recycled material and an average reduction of 18,873 CO_2 emission (kg CO_2-eq).

In Type D2 scenario, the tonnes of recycled material could increase up to 10,790 by adding 2 people to the testing facility, increasing the number of recycling machines from 3 to 4 and keeping the same number of staff in the recycling process. The profits for recycled material, second-life batteries and remanufacturing batteries increased by approximately 18%. Likewise, the CO_2 emissions reductions increased by 18%.

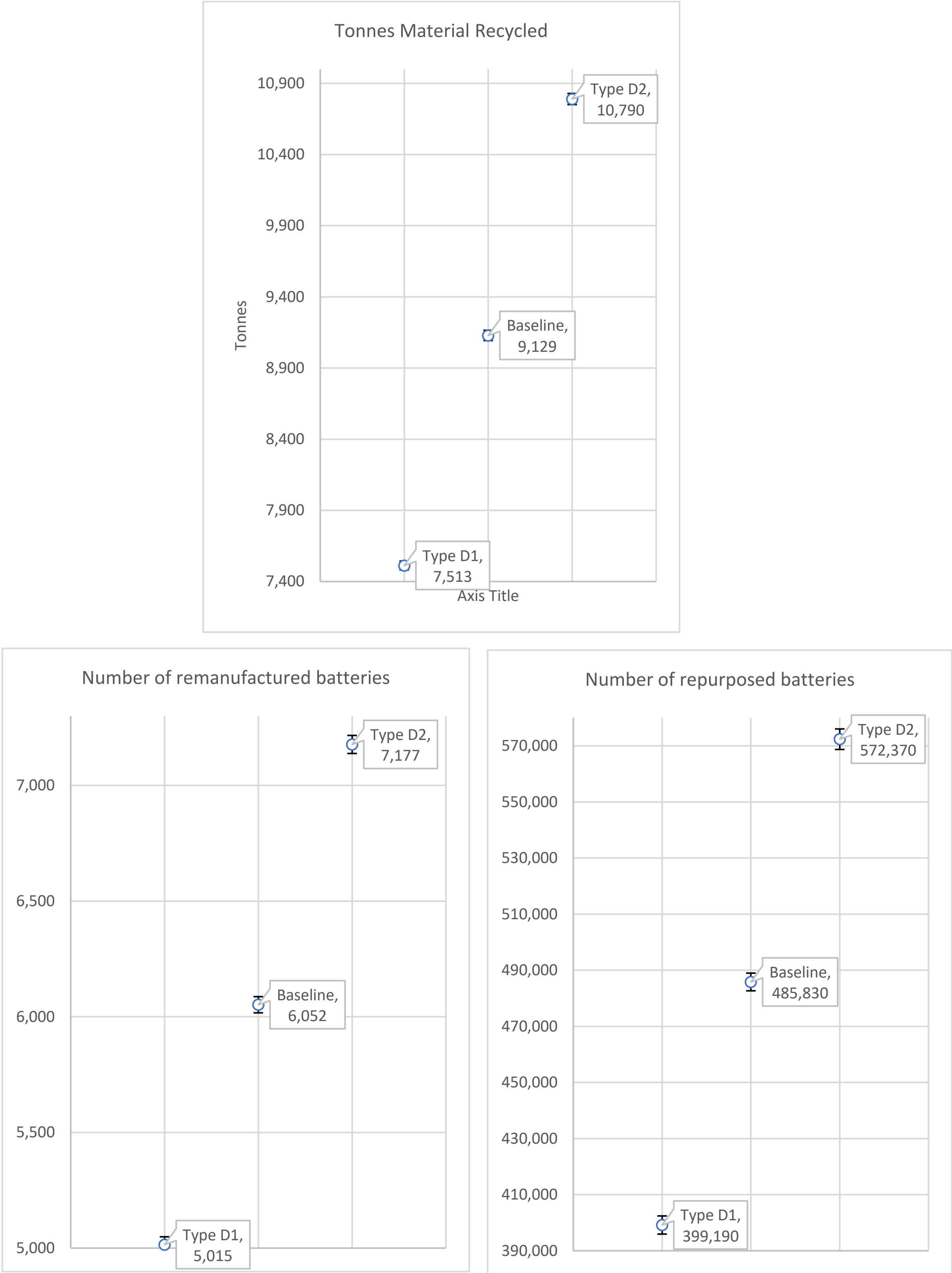


Figure 8.17. Scenarios Type D - Boxplots Tonnes of material recycled, Number of remanufactured batteries and repurposed batteries

Table 8.16 shows a summary of the economic and environmental impact of each of the Type D experiments.

Table 8.16. Scenarios Type D - Economic and environmental impact (Author, 2024)

	Type D1 (2033)	Baseline (2035)	Type D2 (2037)
Profit sales of recycled material (k£) (Average)	15,026	18,258	21,580
CO_2 emission reduction (kg CO_2-eq) (Average)	18,783	22,823	26,975
Savings due to remanufacturing (k£) (Average)	4,514	5,447	6,459
CO_2-eq emission reduction (kg CO_2-eq) (Average)	17,828	21,515	25,514
Savings due to repurposing (k£) (Average)	44,909	54,656	64,392
CO_2 emission reduction (kg CO_2-eq) (Average)	28,382	34,543	40,696

Table 8.17 shows a summary of the staff headcount assigned to each facility and their correspondent utilisation for each scenario.

Table 8.17. Scenarios Type D - Staff and Staff utilisation (Author, 2024)

		Type D – Demand		
		Type D1 (2033)	**Baseline (2035)**	**Type D2 (2037)**
Staff	DealerCentreStaff	10	12	13
	ATFStaff	3	3	4
	TestFacilityStaff	14	15	17
	RemanufStaff	9	9	11
	RecyclerStaff	2	2	2
	RepurposingStaff	20	22	28
Staff Utilisation	RecyclerStaff.ScheduledUtilization	57%	69%	80%
	RepurposingStaff.ScheduledUtilization	71%	79%	73%
	TestFacilityStaff.ScheduledUtilization	64%	77%	75%
	RemanufStaff.ScheduledUtilization	79%	79%	76%
	ATFStaff.ScheduledUtilization	59%	79%	63%
	DealerCentreStaff.ScheduledUtilization	70%	72%	78%

8.10. Discussion simulation experiments

A simulation model was built to represent the EoL RSC for EV batteries and asses the sustainability impact of different groups of scenarios. The first two scenarios, Type A – Reduced disassembling time and Type B – Reduced testing time, were selected based on the sustainability strategies discussed in **Chapter 7. Findings and discussion from the cross-case study analysis**. Disassembling and testing were highlighted as two of the most time-consuming activities for companies involved in the EoL management of batteries. As the case study participants suggested, they have several ongoing collaborative projects and plans to reduce the disassembling and testing time to be able to increase the throughput of batteries. The simulation model proved to be useful and flexible enough to include changes in disassembling time, testing time, and resources assigned to each activity across the EoL RSC.

Another important element that the simulation model can capture is the changes in the proportion of batteries routed for remanufacturing, repurposing and recycling. As the study participants suggested, there is no certainty about the proportion of batteries that would follow the recycling, remanufacturing and repurposing routes. Moreover, the model proved to be flexible enough to input different volumes of batteries. The EoL routes for batteries and the future volume of batteries will be highly dependent on the UK battery legislation and market availability. If legislations promote recycling, the percentage of batteries that follow the recycling route would increase. Whereas if the legislation would set up remanufacturing or repurposing targets, the proportions of batteries following such routes may increase. Moreover, any further changes in the UK government's petrol car ban, like the one presented by the British government in September 2023 (Reuters, 2023) could affect the number of EVs entering the market and the number of EoL EV batteries returning from the market.

Similarly, the proportion of batteries sent to remanufacturing and repurposing will depend on the market available for such products. If the technology and chemistry continue evolving at a fast pace, by the time the batteries return from the market, the OEMs may require different batteries. In the case of repurposed batteries, the market for them is still in its infancy.

The participants mentioned that they have been studying and assessing the different EoL processes in isolation but have not seen a model of the whole RSC for EV batteries before. Having a visual flexible model able to represent a future supply chain that does not exists would allow them to assess a range of potential RSC configurations that follow different processes, routes and volumes was considered important for the study participants. Moreover, the model proved to be useful to assess the impact of different RSC configurations that follow different sustainability strategies in terms of throughput, resources required, capacity (number of batteries processes, tonnes of material recycled, remanufactured batteries, repurposed batteries) and sustainability impact of changes (economic savings, CO_2 impact).

The study participants agreed that the metrics shown in the simulation model study would allow them to conduct more accurate cost-benefit analysis to make well-informed RSC design decisions.

9. Conclusions

9.1. Introduction

The last chapter starts with a summary of the research. Then, the research questions and objectives are revisited. After that, the chapter discusses the theoretical and practical implications. Finally, the limitations and research opportunities are presented.

9.2. Research Summary

The development of a sustainable supply chain has become relevant for companies during the last decade due to environmental, legal, social and economic pressures (Kazemi, Modak and Govindan, 2019). As the literature suggests, an alternative to ensure the sustainability of supply chains and assure their economic viability is the development of sustainable reverse supply chains (Govindan, Soleimani and Kannan, 2015; Kazemi, Modak and Govindan, 2019). A Reverse supply chain consists of all the parties and processes involved in collecting products from a customer to recover value or dispose of them (Guide Jr. and Van Wassenhove, 2002).

Authors like Lind, Olsson and Sundi (2014); Flygansvaer, Dahlstrom and Nygaard, 2018) have conducted empirical RSC studies focused on developed industries with mature RSCs, such as electronics, automotive, metal scrap, packaging materials, paper and apparel. However, emergent RSC have received limited attention. In contrast to mature supply chains, emergent supply chains are characterised by having unstable supply and demand, undefined processes, constant technological changes and limited companies. Hence, there is an opportunity to expand the supply chain, particularly the RSC literature, by conducting a study in an emerging RSC to gain new insights.

This research explores how companies in an emerging RSC like the EoL RSC for EV batteries can develop and design a sustainable EoL reverse supply chain. As presented in Chapter 2 Literature review, previous research has addressed the reverse supply chain design topic by proposing models (see, for example, Jindal & Sangwan, 2014; Ghorbani et al., 2014; Das & Dutta, 2015; Jayant et al., 2014; Yanikara & Kuhl, 2015). Some useful simulation models that address the RSC design were found in the literature (see Jayant et al., 2014; Yanikara & Kuhl, 2015). However, previous RSC design studies have mainly focused on the quantitative aspect and ignored other variables that affect the design, such as the industry context, legislation, technological developments, supplier relationships, resources and capabilities. As discussed in Chapter 3. Theoretical perspective, the review of academic papers showed that only a few authors have used well-established theories to guide sustainable and reverse supply chain research (e.g. Ashby, 2018; Kalaitzi et al., 2019; Madadi et al., 2013; Masoumik et al., 2014; Aristides Matopoulos et al., 2015; Miemczyk et al., 2016; Wong et al., 2012). Natural Resource Based View was one of the theories found in the literature that has been used successfully in the sustainable and reverse supply chain context.

The research questions developed for this study are:

- ***RQ1:*** *What are the requirements for designing a sustainable EoL RSC in an emerging sector?*
- ***RQ2:*** *How can an EoL RSC be designed to meet operational and sustainability objectives?*

Chapter 4. shows the conceptual framework influenced by NRBV and its three path dependency strategies (i.e. pollution prevention, product stewardship and sustainability development), which was used to guide this this research and to explore how companies of an EoL RSC can develop and design a sustainable EoL reverse supply chain. The proposed general framework is based on three main constructs: Drivers and barriers to the implementation of environmental strategies, Reverse supply chain elements (processes, business relationships) and Sustainable Reverse supply chain. The first construct, "Drivers and barriers to the implementation of environmental strategies", is critical to understanding the industry context and the most important factors that influence the development of a reverse supply chain. Then, the second construct, "Reverse supply chain elements", is used to study the current situation of the emerging EoL reverse supply chain through the main EoL processes, main actors and business relationships. Finally, after setting the context and current situation of the EoL RSC, the third construct, "Sustainable Reverse supply chain" is used to identify the potential sustainability strategies to be implemented.

Chapter 5 describes in detail the research design followed in this research. A mixed-methods sequential exploratory case study approach with two main phases that combine qualitative and quantitative methods was chosen since it was considered more appropriate to understand better the research problem chosen. In the first phase, qualitative data is collected from interviews with managers and directors of **Remanufacturer_A** - a Remanufacturing company, **Recycler_A** - Material recycling company, **ScrapCarRecycler_A** - A scrap recycling company that has a national Authorised Treatment Facility (ATF) network, **Repurposer_A** - A company that has been using EV battery cells for second-life applications and OEM_A – Automototive company with presence in UK. The main purpose of the interviews aim to understand the current situation of the UK EoL electric vehicle battery supply chain and the main drivers and barriers to reverse supply chain implementation. The interview insights are also used to understand the main EoL processes, the role of the main RSC stakeholders, and future sustainability strategies. The final phase of the mixed-methods involves collecting quantitative data through interviews and questionnaires and a facilitated modelling intervention to a group of supply chain managers engaged in the electric vehicle battery industry (i.e. **Client_AC** - Automotive company, **Client_RG** -Recycling group, **Client_EC**- Engineering company, **Client_CF**- Consultancy Firm specialised in lithium-ion battery and electric vehicle supply chain, **Client_CF2**- Consultancy Firm specialised in circular economy projects). The second phase aims to build a simulation model that industry practitioners can use to model an emerging EoL reverse supply chain and measure the effect of design changes in terms of economic and environmental impact.

The outcomes of Chapter 6. Findings from case studies in the UK EoL RSC EV batteries, Chapter 7. Findings and discussion from the cross-case study analysis and Chapter 8. Simulation study analysis and discussion are detailed in the following subsection.

9.3. Revisiting the research questions and objectives

This section elaborates on the answers to the research questions formulated at the beginning of this study and how they were addressed in Chapters 6, 7, and 8.

Chapter 6 presents the findings from the individual case studies in the UK EoL RSC EV batteries, which are structured using the framework developed in Chapter 4. Chapter 7 presents the findings and discussion of the cross-case study analysis of the EoL RSC for EV batteries and elaborates on the findings for each of the constructs of the conceptual framework (i.e. Drivers and barriers for the implementation of environmental strategies, EoL RSC elements - processes, business relationships, Sustainable EoL RSC.). Moreover, the perceived influence between the three constructs is analysed to answer the first research question.

Chapter 8 elaborates on the simulation study developed for this research. This chapter explains the process followed to conduct the simulation study. The proposed simulation model was used to test different RSC configurations and assess the impact of changes in terms of throughput, resources, capacity, and economic and environmental impact.

RQ1: What are the requirements for designing a sustainable EoL RSC in an emerging sector?

This study focuses on developing a sustainable EoL reverse supply chain like the EoL EV battery industry, which is in an emerging stage to expand the research insights in the field that has previously focused on mature industries. Five case studies were conducted and analysed to understand how companies from an emerging industry can develop sustainable RSC. The empirical findings of five case studies conducted with key stakeholders of the EoL reverse supply chain for EV batteries were analysed using a framework based on the NRBV theoretical lenses.

The study findings suggest that the lack of efficiency across the EoL processes and EoL market uncertainty strongly influence the sustainability of the RSC for EV batteries. It was identified that a critical operational problem in the EoL processes, such as battery disassembling and battery/modules/cell testing, affects the efficiency and sustainability of the RSC. As the case study findings suggest, these problems are caused by a limited understanding of the configurations and initial SOH of batteries and components. EoL management companies like the ones interviewed in this study suggest that they do not have access to EV battery configuration and SOH information since battery manufacturers do not share this information. In addition, the characteristics of the emerging industry and technological advances of a product such as EV batteries require them to adopt collaboration strategies to improve efficiency. Moreover, to develop EoL solutions that are sustainable and commercially viable, it is necessary to test solutions in potential markets.

Therefore, the study findings suggest that emerging EoL RSC need a group of requirements to design a sustainable EoL RSC, as described in the propositions below, which were discussed in detail in Section 7.7.2. Propositions.

> ***Proposition 1:*** *In emerging RSCs, regulatory frameworks are needed to ensure manufacturers share critical product information to develop sustainable EoL processes.*
>
> ***Proposition 2:*** *In emerging RSCs, early supplier involvement and collaboration among EoL RSC parties and stakeholders are required to develop efficient EoL processes.*
>
> ***Proposition 3:*** *In emerging RSCs, pilots in field applications are required to test EoL solutions and open market opportunities.*

RQ2: How can an EoL RSC be designed to meet operational and sustainability objectives?

The five case studies and simulation study had, in total, the participation of eleven industry stakeholders. The study participants were selected because of their wide knowledge of the different EoL EV batteries RSC processes and experience working on EoL EV battery projects and pilots. The insights from the industry stakeholders allowed the researcher to model a potential UK EoL reverse supply chain that is in an emerging stage and assess different RSC configurations in terms of throughput, resources, capacity and economic and environmental impact.

The mix-methods approach used in this research allowed the researcher to design a model of an EoL reverse supply chain that accounts for the impact of the industry context (i.e. Drivers and barriers for implementing environmental strategies, EoL Reverse supply chain elements and Sustainable Reverse supply chain strategies). This research proposes a simulation model that industry practitioners can use to model an emerging EoL reverse supply chain and measure the effect of design changes in terms of operational, economic and environmental impact. Due to the emerging nature of the RSC selected for this research, the simulation study proposes using a combination of data collection sources such as interviews, questionnaires, and facilitative modelling sessions to capture insights from key industry stakeholders. The simulation model developed for this research proved to be useful for industry stakeholders that participated in the study, and the simulation study results demonstrated that the model could be used to represent an emerging RSC configuration and assess the impact of changes (i.e. collaboration strategies EoL routes variation and future demand) in terms of throughput, resources, capacity (number of batteries processes, tonnes of material recycled, remanufactured batteries, repurposed batteries) and economic and environmental impact of changes (economic savings, CO_2 impact). The study participants agreed that these metrics of the simulation model proposed would allow them to conduct more accurate what-if scenarios by adapting the RSC configuration of the model to assess the impact of different strategies and measure the variation of the metrics (i.e. throughput, resources, capacity, economic saving and CO_2 emissions) in the whole EoL RSC. Having visibility of the whole EoL RSC for EV batteries was considered helpful for the industry stakeholders since their assessment currently focuses on individual subprocesses (i.e., recycling, remanufacturing, and repurposing).

At the beginning of this research, three objectives were established to provide direction and ensure that the research questions were adequately addressed. Table 9.1 presents a concise overview of the research goals and indicates the specific chapter in which each objective was addressed.

Table 9.1. Fulfilment of research objectives

N°	Objective	Chapter
I.	To identify the requirements to design a sustainable EoL RSC	Chapter 6 and Chapter 7
II.	To develop a framework that can support identifying requirements to design a sustainable EoL RSC.	Chapter 4 and Chapter 7
III.	To develop a modelling tool to support the EoL RSC design and assessment of operational, economic and environmental sustainability objectives.	Chapter 8

9.4. Theoretical contribution

This study makes several contributions to the current literature. Firstly, this research contributes to the knowledge by demonstrating the applicability of the NRBV theory to guide the study of the RSC design of an emerging supply chain and complements previous research that has used NRBV in the sustainable supply chain and closed-loop supply chain domain (Masoumik *et al.*, 2014; Miemczyk, Howard and Johnsen, 2016; Ashby, 2018). The use of NRBV as a theoretical lens proved to be useful in gaining insights on how companies of an emerging EoL RSC can develop and design a sustainable EoL reverse supply chain considering the industry context and RSC lifecycle stage.

As Govindan, Soleimani and Kannan (2015); Kazemi, Modak and Govindan (2019)suggest, developing a reverse supply chain is an important mechanism to ensure the sustainability of a product's supply chain. Moreover, as it was identified in the literature, the development of an EoL RSC for EV batteries is even more crucial due to the shortage and increasing price of raw materials used in battery production (International Energy Agency, 2018; Moores, 2018), potential environmental harm if not disposed properly, (Winslow, Laux and Townsend, 2018; International Energy Agency, 2019), and EoL management battery regulations (European Commission, 2023). According to the case study findings, building a RSC for EV batteries is not enough to ensure the sustainability of the supply chain. Therefore, this study contributes to the RSC literature with a research framework that was tested in challenging context like the UK EV batteries RSC to identify what companies involved in an emerging RSC need to make their supply chain more sustainable. This study proposed a framework influenced by the NRBV (Hart, 1995) with three main constructs which allowed a better understanding of the industry and helped to identify the conditions to make it sustainable (i.e.“Drivers and barriers to the implementation of environmental strategies", "Reverse supply chain elements" and "Sustainable Reverse supply chain").

This study contributes to the body of literature on reverse supply chain design with an study in the EV battery sector. This research expands previous RSC literature focused on mature industries such as electronics, automotive, metal scrap, packaging materials, paper and apparel (Lind, Olsson and Sundin, 2014; Flygansvaer, Dahlstrom and Nygaard, 2018). This study shows important insights from an emerging EoL RSC like the EV battery EoL RSC that poses challenges such as unpredictable supply and demand, undefined processes, developing technologies and a reduced number of supply chain actors (Sebastiao and Golicic, 2008; MacCarthy *et al.*, 2016).

Finally, this research proposes the use of a mixed-methods approach and a novel facilitative simulation model used in an industry case study that complements previous RSC modelling that has mostly used linear and non-linear modelling and illustrative cases with created data without a thoughtful understanding of the industry context (see, for example, Jindal & Sangwan, 2014; Ghorbani et al., 2014; Das & Dutta, 2015, Jayant et al., 2014; Yanikara & Kuhl, 2015). The facilitative modelling approach proved to be useful in this case study to represent a RSC in an emerging stage with limited historical data. This research expands previous literature that has used facilitative modelling techniques in education, healthcare and logistics context (Robinson, 2001; Den Hengst, De Vreede and Maghnouji, 2007; Tako and Robinson, 2010) with an example of how the facilitative modelling approach can be used in a RSC context.

9.5. Practical and policy implications

9.4.1. Practical implications

Simchi-Levi (2014) and Sodhi and Tang (2014) suggest that the models from a real industry context are more valid and generalizable to practice. Therefore, this research studies RSC design issues in a real and challenging industry context, like the emerging EoL RSC of EV batteries. The study participants suggested they need tools to assess RSC, like the EV battery RSC, where there is limited historical data in demand, undefined processes are constantly evolving, and uncertainty of future RSC configurations due to changing legislations and battery technological advances. This paper uses a mixed-method approach and a discrete-event simulation tool, such as questionnaires, interviews, and a facilitative intervention that practitioners may use to model a sustainable EoL RSC in an emerging stage with limited historical data. The simulation model proposed can be used to assess changes in the RSC design configurations (i.e. processes, EoL routes, demand levels) and measure the impact in terms of throughput, capacity (number of batteries processes, tonnes of material recycled, remanufactured batteries, repurposed batteries) and sustainability impact of changes (economic savings, CO_2 impact).

As the study findings suggest, developing an EoL RSC in an emerging industry context demands investment in technology, facilities, process improvement, training and resources. For this reason, the simulation model tool can be used to represent an EoL RSC configuration and obtain valuable metrics in terms of capacity planning and economic and environmental metrics that were validated by the industry experts who participated in this study. The versatility of the simulation model and results can be used to develop business cases with different what-if design scenarios and make informed RSC design decisions, taking into consideration the operational impact of changes, RSC capacity requirements and economic savings and the variation of CO_2 emissions across the whole RSC and not only at a sub-process level (i.e. recycling, remanufacturing, repurposing) as it is currently done.

Moreover, this research uses an animated simulation model that can be easily understood and adapted by practitioners in terms of routes, processes, facilities, resources (e.g. workers, machines), and type of entities (i.e. batteries) to represent an emerging RSC of not only the EV battery industry but any industry.

As the case study participants suggested, the adaptability and flexibility of a simulation model are critical in the EV battery context since the future of the RSC is still uncertain and will depend on battery legislation, government approach towards electrification, EV battery technology (e.g. lithium-ion, hydrogen fuel). The model proposed can be posteriorly adapted to represent several design scenarios and assess throughput, capacity and environmental and economic impact.

9.4.2. Policy implications

Regarding policy implications, the most recent regulation is the Regulation (EU) 2023/1542 on batteries and waste batteries published in July 2023 (European Commission, 2023), which defines responsibilities for the EoL management of EVs and EV batteries, suggests processes that need to be followed when batteries reach their EoL and set collection targets. However, as identified in the case studies, the study participants agreed that the current regulations do not enforce information sharing for EoL management purposes(EV battery/components disassembling guidelines, initial SOH information). Moreover, even though the new Regulation (EU) 2023/1542 of the European Parliament and of the Council concerning batteries and waste batteries (European Commission, 2023) mentions that batteries can be repurposed and remanufactured, according to the case study findings, approvals to ship and use each of the batteries' components in the UK aftermarket are still complex and take long periods. Therefore, this research provides a framework and relevant industry-based findings that policymakers can use to have a better understanding of the challenges that the emerging UK EoL RSC of batteries is facing in order to develop policies that benefit EoL management companies and encourage the development of a sustainable UK EoL RSC. For instance, as explained in the discussion section, companies in the EoL RSC for EV batteries need regulatory frameworks that incentivise manufacturers to share EV battery EoL handling/disassembling guidelines and initial product/component State of health (SOH) to increase the throughput and percentage of material/components recovered. In addition, Remanufacturing and Repurposing need regulations encouraging OEMs to remanufacture and repurpose EoL products and ease approval to process, transport and commercialise EoL products and components.

9.5. Limitations and Future Research Opportunities

This paper provides a novel contribution to the RSC literature, but it is not without limitations. Firstly, Using a case study in a specific industry, such as the EV battery industry, as an example may be seen as a limitation because the designs and characteristics of RSCs differ between industries. In addition, doing a case study within a specific industry restricts the ability to extrapolate the findings to other companies and industries. Future studies would be enhanced by incorporating participants from diverse industries to verify the applicability of the research technique and framework in other industry situations. By expanding the range of sectors examined, the researchers could enhance the depth of their research findings by comparing the RSC of other businesses. This would also enable researchers to make generalisations based on their results.

Another characteristic of the UK EV battery industry is its few EoL service providers and competitors. Hence, despite engaging with key stakeholders with industry experience and management expertise leading ATFs, Recycling, Remanufacturing and Repurposing companies, and OEMs, future research would benefit from including more industry participants from the EV battery industry. For future research, the number of industry participants could be increased to gain new insights from other OEMs, remanufacturers, recyclers, and ATFs in the sector with different maturity levels and different perspectives on the problem under study to be able to enrich the framework and simulation model proposed in this research. Furthermore, it would be beneficial for future research to incorporate research institutes engaged in projects that are developing methods for managing end-of-life EV batteries. Including insight from research institutions would provide a deeper understanding of the most current practices, industry partnerships, and technologies that may be employed in the industry in the coming years. Further research on the EoL of EV batteries might be carried out in various regions, including Europe, America, and Asia. Conducting empirical studies in different contexts would provide valuable insights and the opportunity to find best practices from more established companies and mature RSCs.

Another limitation of the simulation model is related to the assumptions used for the quantity of facilities and distance between facilities. This study presents an initial simulation model for representing the EoL RSC for EV batteries. To simplify the model and make it more abstract, the researcher assumes the presence of one dealer repair centre, one ATF, one test facility, one remanufacturing company, one repurposing firm, and one material recycler. Future research could collect additional data to enhance the simulation model and modify the model to incorporate the quantity and location of decentralised facilities where the batteries are processed and the corresponding transport implications (i.e. transport time, cost and CO_2 impact).

Appendix I - Interview Protocol Simulation Study

1. *General information*
    - Could you give a brief introduction about your company?
    - What are the main business activities performed by your company?

2. *Processes*
    - How many facilities do you have? What are the main processes that take place there?
    - Could you explain in detail the processes required to collect/recycle/remanufacture/repurpose an electric vehicle battery?
    - What are the main resources of your facility? Do you require specialised workers? Do you need special machines or equipment?
    - What is your current production capacity? Are you planning to expand it?
    - What is the most time-consuming activity related to the processing of returned batteries/components? Why?
    - What is the most expensive activity related to the processing of returned batteries? Why?

Appendix II - Simulation Study Questionnaire

To build this simulation model, I would require some general information about the main EoL processes. The data for this study can be averages, estimations, and industry figures. The idea is to create a model close to a real industry context; however, there is no need to use data that may be considered sensitive.

Table 1 summarises the process time data required to create the initial process map and simulation model.

Table 1. Processing time

	Processing Time		
Dealer Service centre	Battery removal:		minutes
ATF	Battery removal:	-	minutes
Test Facility	Discharge:		minutes/60 modules*
	Diagnosis:		minutes
	Disassembly for recycling:		minutes
	Disassembly for harvesting:		minutes
Remanufacturer/ Refurbisher	Refurbishing:		minutes
	Cell exchange:		minutes
	Battery assembly:		minutes
Recycler	Battery removal:	-	minutes

Table 2 summarises the resource information required to create the initial process map and simulation model.

Table 2. Resources availability

	Resource availability			
	Number of human resources		Resources schedule	
Dealer Service centre		workers		Hours/day
				working days/week
				£/hour
ATF	-	workers	-	Hours/day
			-	working days/week
			-	£/hour
Test Facility		workers		Hours/day
				working days/week

				£/hour
Remanufacturer/ Refurbisher		workers		Hours/day
				working days/week
				£/hour
Recycler	-	workers	-	Hours/day
			-	working days/week
			-	£/hour

Table 3 summarises the information related to the decision points to create the initial process map and simulation model.

Table 3. Decision points

	Decision points		
Proportion of batteries returned to Dealers and ATFs?	Dealer		%
	ATF		%
Need of discharge?	Yes		%
	No		%
EOL alternative?	Recycling		%
	Harvesting		%
	Remanufacturing/Refurbishing		%
Need of cell exchange?	Yes		%
	No		%

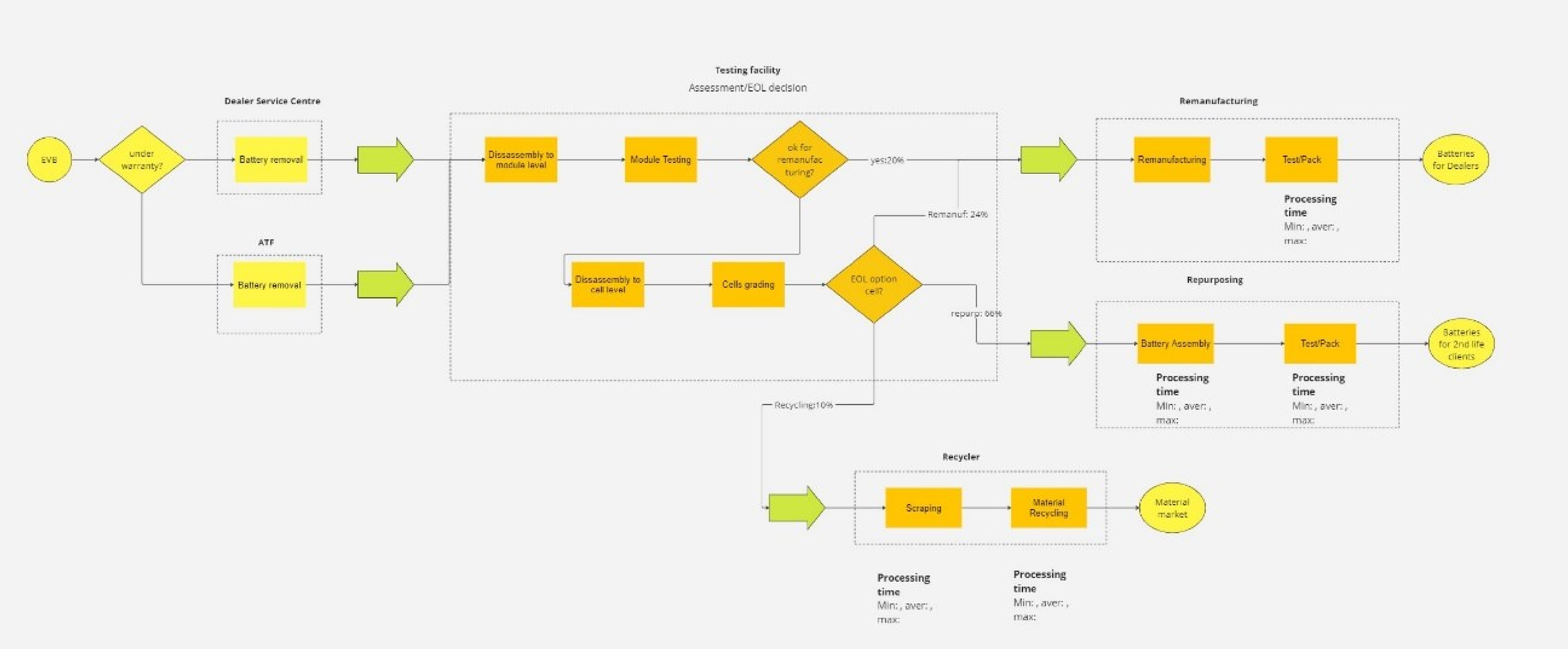
Appendix III - Forecast OEM EoL Batteries

Year	Total New car registration (Thousands)	BEV registration (units)	BEV registration (Thousands)	Market share	Market share BEV (%)	EOL batteries (units)	EoL Batteries OEM
2001	2,586	82	0	0.00%	0.00		
2002	2,682	64	0	0.00%	0.00		
2003	2,646	40	0	0.00%	0.00		
2004	2,599	90	0	0.00%	0.00		
2005	2,443	226	0	0.01%	0.01		
2006	2,340	323	0	0.01%	0.01		
2007	2,390	450	0	0.02%	0.02		
2008	2,112	220	0	0.01%	0.01		
2009	1,968	182	0	0.01%	0.01	82	8
2010	1,996	256	0	0.01%	0.01	64	6
2011	1,907	1,204	1	0.06%	0.06	40	4
2012	2,011	1,680	2	0.08%	0.08	90	9
2013	2,225	2,619	3	0.12%	0.12	226	23
2014	2,438	6,655	7	0.27%	0.27	323	32
2015	2,602	9,833	10	0.38%	0.38	450	45
2016	2,665	10,272	10	0.39%	0.39	220	22
2017	2,509	13,692	14	0.55%	0.55	182	18
2018	2,342	15,579	16	0.67%	0.67	256	26
2019	2,295	37,605	38	1.64%	1.64	1,204	120
2020	1,620	106,682	107	6.59%	6.59	1,680	168
2021	1,640	188,143	188	11.47%	11.47	2,619	262
2022*	2,241	324,888	325	14.5%	14.50	6,655	666
2023*	2,231	309,486	309	13.87%	13.87	9,833	983
2024*	2,221	354,004	354	15.94%	15.94	10,272	1,027
2025*	2,212	398,126	398	18.00%	18.00	13,692	1,369
2026*	2,202	441,851	442	20.06%	20.06	15,579	1,558
2027*	2,193	485,181	485	22.13%	22.13	37,605	3,761
2028*	2,183	528,114	528	24.19%	24.19	106,682	10,668

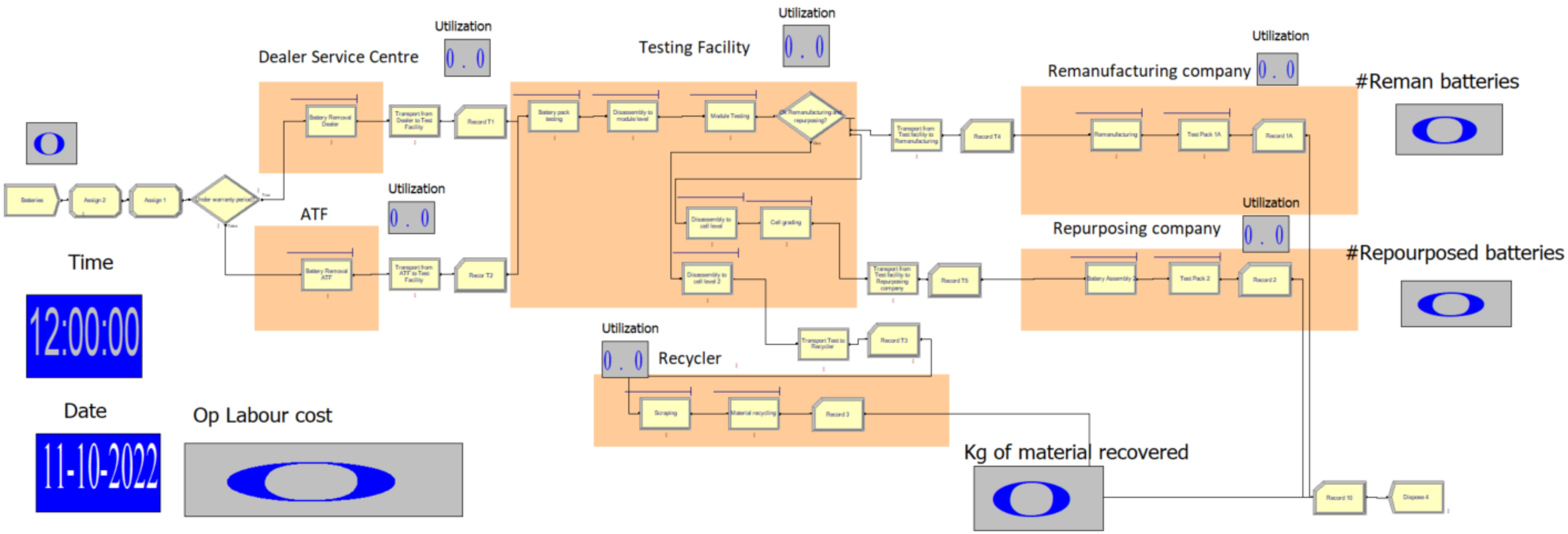
2029*	2,173	570,651	571	26.26%	26.26	188,143	18,814
2030*	**2,164**	**612,792**	**613**	**28.32%**	**28.32**	**324,888**	**32,489**
2031*	2,154	654,536	655	30.38%	30.38	309,486	30,949
2032*	2,145	695,884	696	32.45%	32.45	354,004	35,400
2033*	2,135	736,836	737	34.51%	34.51	398,126	39,813
2034*	2,125	777,391	777	36.58%	36.58	441,851	44,185
2035*	**2,116**	**817,551**	**818**	**38.64%**	**38.64**	**485,181**	**48,518**
2036*	2,106	857,314	857	40.70%	40.70	528,114	52,811
2037*	2,097	896,680	897	42.77%	42.77	570,651	57,065
2038*	2,087	935,651	936	44.83%	44.83	612,792	61,279
2039*	2,077	974,225	974	46.90%	46.90	654,536	65,454
2040*	2,068	1,012,403	1,012	48.96%	48.96	695,884	**69,588**

**Forecasted values*

Appendix IV - Process map Facilitated modelling session



Appendix V - Complete Simulation model



References

Aarikka-Stenroos, L. *et al.* (2022) 'Companies' circular business models enabled by supply chain collaborations: An empirical-based framework, synthesis, and research agenda', *Industrial Marketing Management*, 105(December 2020), pp. 322–339. doi: 10.1016/j.indmarman.2022.06.015.

Abid, S., Hadji, S. and Mhada, F. Z. (2019) 'Simulation Techniques Applied in Reverse Logistic : A Review', *12th International Colloquium of Logistics and Supply Chain Management*, pp. 12–14.

Abraham, N. (2011) 'The apparel aftermarket in India - a case study focusing on reverse logistics', *Journal of Fashion Marketing and Management*, 15(2), pp. 211–227. doi: 10.1108/13612021111132645.

Ackermann, F. (1996) 'Participants' perceptions on the role of facilitators using Group Decision Support Systems', *Group Decision and Negotiation*, 5(1), pp. 93–112. doi: 10.1007/BF00554239.

Ackermann, F. and Eden, C. (2020) 'Strategic Options Development and Analysis', in Reynolds, M. and Holwell (Retired), S. (eds) *Systems Approaches to Making Change: A Practical Guide*. London: Springer London, pp. 139–199. doi: 10.1007/978-1-4471-7472-1_4.

Ackoff, R. L. (1979) 'The Future of Operational Research is Past', *Journal of the operational research society*, 30(2), pp. 30(2): 93–104.

Adamides, E. D. and Karacapilidis, N. (2006) 'A knowledge centred framework for collaborative business process modelling', *Business Process Management Journal*, 12(5), pp. 557–575. doi: 10.1108/14637150610690993.

AESC (2023) *Our Plant*. Available at: https://aesc.co.uk/about/what-we-do/our-plant/.

Airike, P. E., Rotter, J. P. and Mark-Herbert, C. (2016) 'Corporate motives for multi-stakeholder collaboration- corporate social responsibility in the electronics supply chains', *Journal of Cleaner Production*, 131, pp. 639–648. doi: 10.1016/j.jclepro.2016.04.121.

Akhavan, R. M. and Beckmann, M. (2017) 'A configuration of sustainable sourcing and supply management strategies', *Journal of Purchasing and Supply Management*, 23(2), pp. 137–151. doi: 10.1016/j.pursup.2016.07.006.

Al-Alawi, M. K., Cugley, J. and Hassanin, H. (2022) 'Techno-economic feasibility of retired electric-vehicle batteries repurpose/reuse in second-life applications: A systematic review', *Energy and Climate Change*, 3(November), p. 100086. doi: 10.1016/j.egycc.2022.100086.

De Angelis, R., Howard, M. and Miemczyk, J. (2018) 'Supply chain management and the circular economy: towards the circular supply chain', *Production Planning and Control*, 29(6), pp. 425–437. doi: 10.1080/09537287.2018.1449244.

Aral, H. and Vecchio-Sadus, A. (2008) 'Ecotoxicology and Environmental Safety Toxicity of lithium to humans and the environment — A literature review', *Ecotoxicology and Environmental Safety*, 70, pp. 349–356. doi: 10.1016/j.ecoenv.2008.02.026.

Ashby, A. (2018) 'Developing closed loop supply chains for environmental sustainability: Insights from a UK clothing case study', *Journal of Manufacturing Technology Management*, 29(4), pp. 699–722. doi: 10.1108/JMTM-12-2016-0175.

Ashby, A., Leat, M. and Hudson-Smith, M. (2012) 'Making connections: A review of supply chain management and sustainability literature', *Supply Chain Management*, 17(5), pp. 497–516. doi: 10.1108/13598541211258573.

Banks, J. *et al.* (2005) *Discrete-Event System Simulation*. 4th edn. Upper Saddle River, NJ: Prentice Hall.

Barney, J. (1991) 'Firm resources and sustained competitive advantage', *Journal of Management*, 17(1), pp. 99–120.

Barratt, M., Choi, T. and Li, M. (2011) 'Qualitative case studies in operations management: trends, research outcomes and future research implications', *Journal of Operations Management*, 29(4), pp. 329–342.

Batista, L. *et al.* (2019) 'Circular supply chains in emerging economies–a comparative study of packaging recovery ecosystems in China and Brazil', *International Journal of Production Research*, 57(23), pp. 7248–7268. doi: 10.1080/00207543.2018.1558295.

Batista, L. *et al.* (2021) 'Improving the sustainability of food supply chains through circular economy practices – a qualitative mapping approach', *Management of Environmental Quality: An International Journal*, 32(4), pp. 752–767. doi: 10.1108/MEQ-09-2020-0211.

BCG (2021) 'Identifying Resource Scarcities in the Race to Sustainability'.

Belvedere, V. and Grando, A. (2017) *Sustainable operations and supply chain management*. 1. John Wiley & Sons, Inc. (Wiley series in operations research and management science). Available at: https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,url,shib,uid&db=cat00594a&AN=aston.b1915669&site=eds-live&authtype=ip,shib&custid=s9815128.

Bernon, M., Tjahjono, B. and Ripanti, E. F. (2018) 'Aligning retail reverse logistics practice with circular economy values: an exploratory framework', *Production Planning and Control*, 29(6), pp. 483–497. doi: 10.1080/09537287.2018.1449266.

Beske, P., Land, A. and Seuring, S. (2014) 'Sustainable supply chain management practices and dynamic capabilities in the food industry: A critical analysis of the literature', *International Journal of Production Economics*, 152, pp. 131–143. doi: 10.1016/j.ijpe.2013.12.026.

BloombergNEF. (2024). Electric Vehicle Outlook 2024.

BloombergNEF (2021) *Electric Vehicle Outlook 2021*. Available at: https://about.bnef.com/electric-vehicle-outlook/.

Bostrom, R. P., Anson, R. and Clawson, V. K. (1993) 'Group Facilitation and Group Support Systems', in *Group support systems new perspectives*, pp. 146–168. doi: 10.1109/HICSS.1993.284182.

Brundtland, G. H. (1987) *Report of the World Commission on environment and development:" our common future"*.

Canals Casals, L., Amante García, B. and Cremades, L. V. (2017) 'Electric vehicle battery reuse: Preparing for a second life', *Journal of Industrial Engineering and Management*, 10(2Special Issue), pp. 266–285. doi: 10.3926/jiem.2009.

Carter, C. and Ellram, L. (1998) 'Reverse Logistics -- a Review of the Literature and Framework for Future Investigation.', *Journal of Business Logistics*, 19(1), pp. 85–102.

Chaabane, A., Ramudhin, A. and Paquet, M. (2012) 'Design of sustainable supply chains under the emission trading scheme', *International Journal of Production Economics*, 135(1), pp. 37–49. doi: 10.1016/j.ijpe.2010.10.025.

Checkland, P. (1981) *Systems Thinking, Systems Practice*. Chichester: Wiley.

Chen, J. M. and Chang, C. I. (2012) 'The co-opetitive strategy of a closed-loop supply chain with remanufacturing', *Transportation Research Part E: Logistics and Transportation Review*, 48(2), pp. 387–400. doi: 10.1016/j.tre.2011.10.001.

Chen, M. *et al.* (2019) 'Recycling End-of-Life Electric Vehicle Lithium-Ion Batteries', *Joule*, 3(11), pp. 2622–2646. doi: 10.1016/j.joule.2019.09.014.

Chen, Q. *et al.* (2022) 'Investigating carbon footprint and carbon reduction potential using a cradle-to-cradle LCA approach on lithium-ion batteries for electric vehicles in China', *Journal of Cleaner Production*, 369(April), p. 133342. doi: 10.1016/j.jclepro.2022.133342.

Chen, Y. T. *et al.* (2018) 'Optimization of product refurbishment in closed-loop supply chain using multi-period model integrated with fuzzy controller under uncertainties', *Robotics and Computer–Integrated Manufacturing*, 50(December 2015), pp. 1–12. doi: 10.1016/j.rcim.2017.05.005.

Choi, T. - M., Cheng, T. C. E. and Zhao, X. (2016) 'Multi-Methodological Research in Operations Management.', *Production & Operations Management*, 25(3), pp. 379–389. Available at: http://10.0.4.87/poms.12534.

Chopra, S. (2019) *Supply chain management: strategy, planning and operation.* Seventh, g. Pearson. Available at: https://search.ebscohost.com/login.aspx?direct=true&db=cat00594a&AN=aston.b1861729&site=eds-live&authtype=ip,shib&custid=s9815128.

Christopher, M. (2016) *Logistics & supply chain management*. Fifth edit. Pearson (Always Learning). Available at: https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,url,shib,uid&db=cat00594a&AN=aston.b1911110&site=eds-live&authtype=ip,shib&custid=s9815128.

Christopher, M. and Peck, H. (2002) *Marketing logistic.* 2nd ed. Butterworth-Heinemann. Available at: https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,url,shib,uid&db=cat00594a&AN=aston.b1072317&site=eds-live&authtype=ip,shib&custid=s9815128.

Cohen, W. M. and Levinthal, D. A. (1990) 'Absorptive Capacity : A New Perspective on Learning and Innovation', *Administrative Science Quarterly,* 35(1), pp. 128–152.

Costa, C. M. *et al.* (2021) 'Recycling and environmental issues of lithium-ion batteries: Advances, challenges and opportunities', *Energy Storage Materials*, 37(February), pp. 433–465. doi: 10.1016/j.ensm.2021.02.032.

Cox, A. (1996) 'Relational competence and strategic procurement management', *European Journal of Purchasing and Supply Management*, 2(1), pp. 57–70. doi: 10.1016/0969-7012(95)00019-4.

Crane, A. and Ruebottom, T. (2012) 'Stakeholder Theory and Social Identity : Rethinking Stakeholder Identification', (2011), pp. 77–87. doi: 10.1007/s10551-011-1191-4.

Crawford, I., Shao-Horn, Y. and Keith, D. (2022) *How much CO2 is emitted by manufacturing batteries?*, *MIT Climate*. Available at: https://climate.mit.edu/ask-mit/how-much-co2-emitted-manufacturing-batteries#:~:text=The production process&text=Particularly in hard rock mining,are emitted into the air.

Creswell, J. W. (2014) *Research design : qualitative, quantitative & mixed methods approaches*. 4th edn. London: SAGE.

Creswell, J. W. and Creswell, J. D. (2018) *Research design : qualitative, quantitative & mixed methods approaches*. 5th edn. London: SAGE. Available at: http://search.ebscohost.com/login.aspx?direct=true&db=cat00594a&AN=aston.b1768649&site=eds-live&authtype=ip,shib&custid=s9815128.

Cricelli, L., Greco, M. and Grimaldi, M. (2021) 'An investigation on the effect of inter-organizational collaboration on reverse logistics', *International Journal of Production Economics*, 240(September 2020), p. 108216. doi: 10.1016/j.ijpe.2021.108216.

Croson, R. *et al.* (2014) 'Order Stability in Supply Chains : Coordination Risk and the Role of Coordination Stock', *Production and Operations Management*, 23(2), pp. 176–196. doi: 10.1111/j.1937-5956.2012.01422.x.

Croson, R., Donohue, K. and Donohue, K. (2006) 'Behavioral Causes of the Bullwhip Effect and the Observed Value of Inventory Information Behavioral Causes of the Bullwhip Effect and the Observed Value of Inventory Information', *Management Science*, (November 2022). doi: 10.1287/mnsc.1050.0436.

Daft, R. L. (1998) *Organization theory and design*. 6th ed. South Western College Publishing (Miscellaneous/Catalogs S). Available at: https://search.ebscohost.com/login.aspx?direct=true&db=cat00594a&AN=aston.b1057509&site=eds-live&authtype=ip,shib&custid=s9815128.

Das, D. and Dutta, P. (2015) 'Design and analysis of a closed-loop supply chain in presence of promotional offer', *International Journal of Production Research*, 53(1), pp. 141–165.

Daugherty, P. J. (2011) 'Review of logistics and supply chain relationship literature and suggested research agenda', *International Journal of Physical Distribution and Logistics Management*, 41(1), pp. 16–31. doi: 10.1108/09600031111101402.

Deloitte LLP (2019) *New market. New entrants. New challenges. Battery Electric Vehicles*.

Denzin, N. K. and Lincoln, Y. S. (2011) *The SAGE handbook of qualitative research.* Thousand Oaks, CA ; London : SAGE, ©2011. Available at: http://search.ebscohost.com/login.aspx?direct=true&db=cat00594a&AN=aston.b1421590&site=eds-live&authtype=ip,shib&custid=s9815128.

Department for transport (2021) *Transport and environment statistics: Autumn 2021*. Available at: https://www.gov.uk/government/statistics/transport-and-environment-statistics-autumn-2021/transport-and-environment-statistics-autumn-2021#:~:text=Transport produced 27%25 of the,transport vehicles (111 MtCO2e).

Department for Transport (2017) *Freight Carbon Review*. London. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/590922/freight-carbon-review-2017.pdf.

Department for Transport (2019) *Domestic Road Freight Statistics, United Kingdom 2018*. London. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/815839/domestic-road-freight-statistics-2018.pdf.

DeRousseau, M. *et al.* (2017) 'Repurposing Used Electric Car Batteries: A Review of Options', *The Journal of The Minerals, Metals & Materials Society*, 69(9), pp. 1575–1582. doi: 10.1007/s11837-017-2368-9.

Dowlatshahi, S. (2010) 'A cost-benefit analysis for the design and implementation of reverse logistics systems: Case studies approach', *International Journal of Production Research*, 48(5), pp. 1361–1380. doi: 10.1080/00207540802552642.

Dubey, B., Townsend, T. and Solo-gabriele, H. (2010) ‘Metal loss from treated wood products in contact with municipal solid waste landfill leachate’, *Journal of Hazardous Materials*, 175, pp. 558–568. doi: 10.1016/j.jhazmat.2009.10.042.

Eden, C. (1982) ‘Problem construction and the influence of OR’, *The Institute of Management Sciences*, 12(2), pp. 50–60.

Eden, C. and Ackermann, F. (2004) ‘Use of ’Soft OR’ models by clients: What do they want from them?’, in *Systems Modelling: Theory and Practice*. Chichester: Wiley, pp. 146–163.

Eden, C. and Radford, J. (1990) *Tackling strategic problems: the role of group decision support*. London: SAGE Publications.

Eden, C. and Sims, D. (1979) ‘On the nature of problems in consulting practice’, *OMEGA: The International Journal of Management Science*, 7(2), pp. 119–127.

EDF (2019) *All about electric car batteries*. Available at: https://www.edfenergy.com/electric-cars/batteries.

Eisenhardt, K. M. (1989a) ‘Agency Theory: An Assessment and Review’, *Academy of Management*, 14(1), pp. 57–74.

Eisenhardt, K. M. (1989b) ‘Building Theories from Case Study Research’, *Academy of Management Review*, 14(4), pp. 532–550. doi: 10.4324/9781351106573-2.

Elkington, J. (1994) ‘Towards the Sustainable Corporation: Win-Win-Win Business Strategies for Sustainable Development’, *California Management Review*, 36(2), pp. 90–100. doi: 10.2307/41165746.

Engel, H., Hertzke, P. and Siccardo, G. (2019) ‘Second-life EV batteries: The newest value pool in energy storage’, *McKinsey & Company*, (April). Available at: https://www.febiac.be/public/statistics.aspx?FID=23.

Euro NCAP (2023) *About European New Car Assessment Program*. Available at: https://www.euroncap.com/en (Accessed: 10 March 2023).

European Commission (2000) *DIRECTIVE 2000/53/EC*, *Official Journal of the European Communities*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02000L0053-20130611&qid=1405610569066&from=EN.

European Commission (2008) ‘Directive 2008/68/EC on the inland transport of dangerous goods’, *Official Journal of the European Union*. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:260:0013:0059:en:PDF.

European Commission (2015) *Guidance Document on the Definition and Classification of Hazardous Waste*. Available at: http://ec.europa.eu/environment/ waste/pdf/consult/Draft guidance document_09062015.pdf.

European Commission (2019) ‘Directive (EU) 2019/771 of the European Parliament and of the Council of 20 May 2019 on certain aspects concerning contracts for the sale of goods, amending Regulation (EU) 2017/2394 and Directive 2009/22/EC, and repealing Directive 1999/44/EC’, *Official Journal of the European Union*, L 136(March), pp. 28–50. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1574673031326&uri=CELEX:32019L0771.

European Commission (2020a) *Directive 2000/53/EC on end-of-life vehicles*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02000L0053-20200306&from=EN.

European Commission (2020b) *Regulation of the European Parliament and of the Council concerning batteries and waste batteries*, *European Commission*. Brussels. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0798.

European Commission (2023) 'Regulation (EU) 2023/1542 of the European Parliament and of the Council concerning batteries and waste batteries', *European Commission*, 2023(June), pp. 1–117. Available at: http://data.europa.eu/eli/reg/2023/1542/oj%0Ahttps://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0798.

European Commission DG for Mobility and Transport (2017) *An Overview of the EU Road Transport Market in 2015*, *European Commission*. Available at: https://ec.europa.eu/transport/sites/transport/files/mobility-package-overview-of-the-eu-road-transport-market-in-2015.pdf.

European Parliament (2020) *Transport CO2 emissions in focus*.

European Parliament. (2022). EU ban on the sale of new petrol and diesel cars from 2035. https://www.europarl.europa.eu/topics/en/article/20221019STO44572/eu-ban-on-sale-of-new-petrol-and-diesel-cars-from-2035-explained

Fleischmann, M. *et al.* (2004) 'Reverse Logistics Network Design', in Dekker, R. et al. (eds). Berlin, Heidelberg: Springe, pp. 65–94. doi: 10.1007/978-3-540-24803-3_4.

Fleischmann, M., Ronald, H. and Dekker, R. (2000) 'A characterisation of logistics networks for product recovery', *OMEGA: The International Journal of Management Science*, 28.

Flygansvaer, B., Dahlstrom, R. and Nygaard, A. (2018) 'Exploring the pursuit of sustainability in reverse supply chains for electronics', *Journal of Cleaner Production*, 189, pp. 472–484. doi: 10.1016/j.jclepro.2018.04.014.

Flynn, B. B. *et al.* (1990) 'Empirical research methods in operations management', *Journal of Operations Management*, 9(2), pp. 250–284. doi: https://doi.org/10.1016/0272-6963(90)90098-X.

Forrester, J. W. (1997) 'Industrial Dynamics', *Journal of the Operational Research Society*, 48(10), pp. 1037–1041. doi: 10.1057/palgrave.jors.2600946.

Forza, C. (2002) 'Survey research in operations management: A process-based perspective', *International Journal of Operations and Production Management*, 22(2), pp. 152–194. doi: 10.1108/01443570210414310.

Foster, M. *et al.* (2014) 'Feasibility assessment of remanufacturing, repurposing, and recycling of end of vehicle application lithium-ion batteries', *Journal of Industrial Engineering and Management*, 7(3), pp. 698–715. doi: 10.3926/jiem.939.

Franco, L. A. and Montibeller, G. (2010) 'Facilitated modelling in operational research', *European Journal of Operational Research*, 205(3), pp. 489–500. doi: 10.1016/j.ejor.2009.09.030.

Freeman, R. E. (1984) *Strategic management: A stakeholder approach*. Boston: Pitman.

Friedman, M. and Friedman, M. (1953) *Essays in Positive Economics*. University of Chicago Press (A Phoenix book. Business economics). Available at: https://books.google.fr/books?id=Fv8846OSbvwC.

General Motors (2015) *Used Chevrolet Volt Batteries Help Power New IT Building*.

Available at:
https://news.gm.com/newsroom.detail.html/Pages/news/us/en/2015/jun/0616-volt-battery.html.

Georgiadis, P. and Besiou, M. (2008) ‘Sustainability in electrical and electronic equipment closed-loop supply chains : A System Dynamics approach’, *Journal of Cleaner Production*, 16, pp. 1665–1678. doi: 10.1016/j.jclepro.2008.04.019.

Ghorbani, M., Arabzad, S. M. and Tavakkoli-Moghaddam, R. (2014) ‘A multi-objective fuzzy goal programming model for reverse supply chain design’, *International Journal of Operational Research*, 19(2), pp. 141–153. doi: 10.1504/IJOR.2014.058947.

Global Battery Solutions (2022) *Battery & Electronics Lifecycle Management*. Available at: https://globalbatterysolutions.com/.

Gobbi, C. (2011) ‘Designing the reverse supply chain: The impact of the product residual value’, *International Journal of Physical Distribution and Logistics Management*, 41(8), pp. 768–796. doi: 10.1108/09600031111166429.

Goldman Sachs. (2024). Lower battery prices are expected to eventually boost EV demand. https://www.goldmansachs.com/insights/articles/even-as-ev-sales-slow-lower-battery-prices-expect

GOV.UK (2023a) *Pathway for zero emission vehicle transition by 2035 becomes law*. Available at: https://www.gov.uk/government/news/pathway-for-zero-emission-vehicle-transition-by-2035-becomes-law.

GOV.UK (2023b) *Tariffs on electric vehicles avoided as UK and EU extend trade rules*. Available at: https://www.gov.uk/government/news/tariffs-on-electric-vehicles-avoided-as-uk-and-eu-extend-trade-rules.

GOV.UK (2023c) *Tata Group to invest over £4 billion in UK gigafactory creating thousands of jobs*. Available at: https://www.gov.uk/government/news/tata-group-to-invest-over-4-billion-in-uk-gigafactory-creating-thousands-of-jobs.

Govindan, K. *et al.* (2019) ‘Environmental management partner selection for reverse supply chain collaboration: A sustainable approach’, *Journal of Environmental Management*, 236(August 2018), pp. 784–797. doi: 10.1016/j.jenvman.2018.11.088.

Govindan, K. and Bouzon, M. (2018) ‘From a literature review to a multi-perspective framework for reverse logistics barriers and drivers’, *Journal of Cleaner Production*, 187, pp. 318–337. doi: 10.1016/j.jclepro.2018.03.040.

Govindan, K. and Hasanagic, M. (2018) ‘A systematic review on drivers, barriers, and practices towards circular economy: a supply chain perspective’, *International Journal of Production Research*, 56(1–2), pp. 278–311. doi: 10.1080/00207543.2017.1402141.

Govindan, K., Paam, P. and Abtahi, A. R. (2016) ‘A fuzzy multi-objective optimization model for sustainable reverse logistics network design’, *Ecological Indicators*, 67, pp. 753–768. doi: 10.1016/j.ecolind.2016.03.017.

Govindan, K., Soleimani, H. and Kannan, D. (2015) ‘Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future’, *European Journal of Operational Research*, 240(3), pp. 603–626. doi: 10.1016/j.ejor.2014.07.012.

Grant, D. B., Trautrims, A. and Wong, C. Y. (2017) *Sustainable logistics and supply chain management: principles and practices for sustainable operations and management.* Second edi. Kogan Page. Available at: https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,url,shib,uid&db=cat00594a&AN=aston.b1912349&site=eds-live&authtype=ip,shib&custid=s9815128.

Greasley, A. (2004) *Simulation modelling for business. [electronic resource]*. Aldershot : Ashgate, 2004. (Innovative business textbooks). Available at: http://search.ebscohost.com/login.aspx?direct=true&db=cat00594a&AN=aston.b1741580&site=eds-live&authtype=ip,shib&custid=s9815128.

Greasley, A. (2019) *Simulating Business Processes for Descriptive, Predictive, and Prescriptive Analytics*. [Boston, Mass.?]: De Gruyter. Available at: https://search.ebscohost.com/login.aspx?direct=true&db=e020mww&AN=2330456&site=eds-live&authtype=ip,shib&custid=s9815128.

Greasley, A. (2023) *Simulation Modelling: Concepts, Tools and Practical Business Applications*. 1st edn. London: Routledge.

Grekova, K. *et al.* (2014) 'Extending environmental management beyond the firm boundaries: An empirical study of Dutch food and beverage firms', *International Journal of Production Economics*, 152, pp. 174–187. doi: 10.1016/j.ijpe.2013.12.019.

Grosvold, J., Hoejmose, S. U. and Roehrich, J. K. (2014) 'Squaring the circle: Management, measurement and performance of sustainability in supply chains', *Supply Chain Management*, 19(3), pp. 292–305. doi: 10.1108/SCM-12-2013-0440.

Gruber, P. W. *et al.* (2011) 'Global Lithium Availability A Constraint for Electric Vehicles ?', *Journal of Industrial Ecology*, 15(5), pp. 760–775. doi: 10.1111/j.1530-9290.2011.00359.x.

Guide, D. R. and Wassenhove, L. N. Van (2009) 'The Evolution of Closed-Loop Supply Chain Research', *Operations Research Forum*, 57(1), pp. 10–18. doi: 10.1287/opre.1080.0628.

Guide Jr., V. and Van Wassenhove, L. (2002) 'The Reverse Supply Chain', *Harvard business review*, 80(2), pp. 25–26.

Gupta, S. M. (2012) *Reverse Supply Chain*. Boca Raton, FL: Taylor & Francis Group. doi: http://dx.doi.org/10.1097/PRS.0b013e3182729ec2.

Hai-jun, M. *et al.* (2007) 'Research on Remanufacturing Reverse Logistics Network Facility', *2007 International Conference on Management Science & Engineering (14th)*, 14, pp. 488–494.

Halldorsson, A. and Aastrup, J. (2003) 'Quality criteria for qualitative inquiries in logistics', *European Journal of Operational Research VO - 144*, (2), p. 321. Available at: http://search.ebscohost.com/login.aspx?direct=true&db=edsggo&AN=edsgcl.151243499&site=eds-live&authtype=ip,shib&custid=s9815128.

Haram, M. H. S. M. *et al.* (2021) 'Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges', *Alexandria Engineering Journal*, 60(5), pp. 4517–4536. doi: 10.1016/j.aej.2021.03.021.

Harrison, A. and van Hoek, R. (2008) *Logistics Management and Strategy: Competing through the supply chain*. 3rd edn, *Strategic Direction*. 3rd edn. Financial Times Prentice Hall. doi: 10.1108/sd.2007.05623cae.001.

Hart, S. L. (1995) 'A Natural-Resource-Based View of the Firm', *The Academy of Management review*, 20(4), pp. 986–1014.

Hart, S. L. and Dowell, G. (2011) 'A Natural-Resource-Based View of the Firm: Fifteen Years After', *Journal of Management*, 37(5), pp. 1464–1479. doi: 10.1177/0149206310390219.

Heelan, J. *et al.* (2016) 'Current and Prospective Li-Ion Battery Recycling and Recovery Processes', *Jom*, 68(10), pp. 2632–2638. doi: 10.1007/s11837-016-1994-y.

Den Hengst, M., De Vreede, G. J. and Maghnouji, R. (2007) 'Using soft OR principles for collaborative simulation: a case study in the Dutch airline industry', *Journal of the Operational Research Society*, 58(5), pp. 669–682. doi: 10.1057/palgrave.jors.2602353.

Hertzke, P., Muller, N. and Schenk, S. (2017) *Dynamics in the global electric-vehicle market*, *McKinsey & Company*. Available at: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/dynamics-in-the-global-electric-vehicle-market.

Hollis, M. (1994) *The philosophy of social science: an introduction.* Cambridge University Press. Available at: http://search.ebscohost.com/login.aspx?direct=true&db=cat00594a&AN=aston.b1787085&site=eds-live&authtype=ip,shib&custid=s9815128.

Honda (2019) *Battery recycling*. Available at: https://apps.honda.co.uk/environment/designingthefuture/batteryrecycling/.

Honda (2020) *Honda Hybrid & EV Batteries get second life in new recycling initiative*. Available at: https://www.honda.co.uk/engineroom/world/hybrid-and-ev-battery-recycling-SNAM/ (Accessed: 10 June 2020).

Huang, Y. C. and Yang, M. L. (2014) 'Reverse logistics innovation, institutional pressures and performance', *Management Research Review*, 37(7), pp. 615–641. doi: 10.1108/MRR-03-2013-0069.

ICCT (2018) 'Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions', *ICCT Briefing*, (February), p. 12. Available at: https://www.theicct.org/sites/default/files/publications/EV-life-cycle-GHG_ICCT-Briefing_09022018_vF.pdf.

International Environmental Agency. (2024). Global EV Outlook 2024 Moving towards increased affordability. www.iea.org

International Energy Agency (2018) *Global EV Outlook 2018*. Available at: https://www.iea.org/reports/global-ev-outlook-2018.

International Energy Agency (2019) *Global EV Outlook 2019*.

Jabbarzadeh, A., Fahimnia, B. and Sabouhi, F. (2018) 'Resilient and sustainable supply chain design: sustainability analysis under disruption risks', *International Journal of Production Research*, 56(17), pp. 5945–5968. doi: 10.1080/00207543.2018.1461950.

Jahangirian, M. *et al.* (2010) 'Simulation in manufacturing and business : A review', *European Journal of Operational Research*, 203(1), pp. 1–13. doi: 10.1016/j.ejor.2009.06.004.

Jayant, A., Gupta, P. and Garg, S. (2012) 'Reverse Logistics: Perspectives, Empirical Studies and Research Directions', *The International Journal of Industrial Engineering: Theory, Applications and Practice*, 19(January), pp. 369–388.

Jayant, A., Gupta, P. and Garg, S. (2014) 'Simulation modelling and analysis of network design for closed-loop supply chain: A case study of battery industry', in *Procedia Engineering*. doi: 10.1016/j.proeng.2014.12.465.

Jensen, M. C. (1983) 'Organization Theory and Methodology', *The Accounting Review*, 58(2), pp. 319–339. doi: 10.2139/ssrn.94036.

Jensen, M. C. and Meckling, W. H. (1976) ‘Theory of the firm: Managerial behavior Agency costs and ownership structure’, *Jourmal of Financial Economics*, 3, pp. 305–360. doi: 10.1177/0018726718812602.

Jindal, A. and Sangwan, K. S. (2014) ‘Closed loop supply chain network design and optimisation using fuzzy mixed integer linear programming model’, *International Journal of Production Research*, 52(14), pp. 4156–4173.

Joshi, S. (2022) ‘A review on sustainable supply chain network design: Dimensions, paradigms, concepts, framework and future directions’, *Sustainable Operations and Computers*, 3(October 2021), pp. 136–148. doi: 10.1016/j.susoc.2022.01.001.

Jowitt, S. M. *et al.* (2018) ‘Recycling of the rare earth elements’, *Green and Sustainable Chemistry*, 13, pp. 1–7. doi: 10.1016/j.cogsc.2018.02.008.

Kabadurmus, O., & Erdogan, M. S. (2020). Sustainable, multimodal and reliable supply chain design. Annals of Operations Research, 292(1), 47–70.

Kalaitzi, D., Matopoulos, A. and Clegg, B. (2019) ‘Managing resource dependencies in electric vehicle supply chains: a multi-tier case study’, *Supply Chain Management*, 24(2), pp. 256–270. doi: 10.1108/SCM-03-2018-0116.

Kang, D., Chen, M. and Ogunseitan, O. (2013) ‘Potential Environmental and Human Health Impacts of Rechargeable Lithium Batteries in Electronic Waste’, *Environmental Science & Technology*, 47, p. file:///C:/Users/mvene/Downloads/1-s2.0-S0304386X0.

Karlsson, C. (2009) *Researching Operations Management*. New York: Routledge.

Kazemi, N., Modak, N. M. and Govindan, K. (2019) ‘A review of reverse logistics and closed loop supply chain management studies published in IJPR: a bibliometric and content analysis’, *International Journal of Production Research*, 57(15–16), pp. 4937–4960. doi: 10.1080/00207543.2018.1471244.

Kerlinger, F. (1979) *Behavioral research: A conceptual approach*. 3rd ed. New York: Holt, Rinehart & Winston. Available at: https://search.ebscohost.com/login.aspx?direct=true&db=cat00594a&AN=aston.b1002275&site=eds-live&authtype=ip,shib&custid=s9815128.

Kirchherr, J., Reike, D. and Hekkert, M. (2017) ‘Conceptualizing the circular economy: An analysis of 114 definitions’, *Resources, Conservation & Recyclin*, 127, pp. 221–232. doi: 10.1016/j.resconrec.2017.09.005.

Kjeldsen, P. *et al.* (2010) ‘Technology Present and Long-Term Composition of MSW Landfill Leachate : A Review Present and Long-Term Composition of MSW Landfill Leachate : A Review’, 3389. doi: 10.1080/10643380290813462.

Kleindorfer, P. R., Singhal, K. and Van Wassenhove, L. N. (2005) ‘Sustainable operations management’, *Production and Operations Management*, 14(4), pp. 482–492. doi: 10.1111/j.1937-5956.2005.tb00235.x.

Klör, B., Bräuer, S. and Beverungen, D. (2014) ‘A business process model for the reverse logistics of used electric vehicle batteries’, *Lecture Notes in Informatics (LNI), Proceedings - Series of the Gesellschaft fur Informatik (GI)*, P-232(January 2014), pp. 1631–1643.

Krause, D., Luzzini, D. and Lawson, B. (2018) ‘Building the Case for A Single Key Informant in Supply Chain Management Survey Research’, *Journal of Supply Chain Management*, 54(1), pp. 42–50. doi: 10.1111/jscm.12159.

Krikke, H., le Blanc, I. and van de Velde, S. (2004) ‘Product Modularity and the Design of Closed-Loop Supply Chains’, *California Management Review*, 46(2), pp. 22–39.

Kumar, N., Stern, L. W. and Anderson, J. C. (1993) ‘Conducting Interorganizational Research Using Key Informants’, *Academy of Management Journal*, 36(6), pp. 1633–1651. doi: 10.2307/256824.

Lambert, D. and Cooper, M. (2000) ‘Issues in supply chain management’, *Industrial Marketing Management*, 29, pp. 65–83. doi: 10.1017/UPO9788175968462.008.

Lambert, D., Cooper, M. and Pagh, J. (1998) ‘Supply chain management: implementation issues and research opportunities’, 9(2), pp. 1–19.

Lambert, D. M., Emmelhainz, M. A. and Gardner, J. T. (1996) ‘Developing and implementing supply chain partnerships, Lambert et al.pdf’, *The International Journal of Logistics Management*, pp. 1–17.

Landry, M. (1995) ‘A Note on the Concept of “Problem”’, *Organization Studies*, 16(2), pp. 315–343. doi: 10.1177/017084069501600206.

Lane, D. (1992) ‘Modelling as learning: A consultancy methodology for enhancing learning in management teams’, *European Journal of Operational Research*, 59(1), pp. 64–84.

Laplume, A. O. and Litz, R. A. (2008) *Stakeholder Theory : Reviewing a Theory That Moves Us*. doi: 10.1177/0149206308324322.

Law, A. (2015) *Simulation Modeling and Analysis*. New York: McGraw-Hill Education.

Lee, N. and Lings, I. (2008) *Doing business research: a guide to theory and practice*. SAGE. Available at: https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,url,shib,uid&db=cat00594a&AN=aston.b1670649&site=eds-live&authtype=ip,shib&custid=s9815128.

Leonard, A., Hantson, P. and Gerber, G. B. (1995) ‘Mutagenicity , carcinogenicity and teratogenicity of lithium compounds’, *Mutation Research/Reviews in Genetic Toxicology*, 339(3), pp. 131–137.

Li, Y. *et al.* (2009) ‘Leaching of heavy metals from E-waste in simulated landfill columns’, *Waste Management*, 29(7), pp. 2147–2150. doi: 10.1016/j.wasman.2009.02.005.

Lima-Junior, F. R. and Carpinetti, L. C. R. (2017) ‘Quantitative models for supply chain performance evaluation: A literature review’, *Computers and Industrial Engineering*, 113(July), pp. 333–346. doi: 10.1016/j.cie.2017.09.022.

Lind, S., Olsson, D. and Sundin, E. (2014) ‘Exploring inter-organizational relationships in automotive component remanufacturing’, *Journal of Remanufacturing*, 4(1), pp. 1–14. doi: 10.1186/2210-4690-4-5.

Lindo Systems (2020) *Lindo Systems*. Available at: https://www.lindo.com/ (Accessed: 1 July 2020).

Lisbona, D. and Snee, T. (2011) ‘A review of hazards associated with primary lithium and lithium-ion batteries’, *Process Safety and Environmental Protection*, 89(6), pp. 434–442. doi: 10.1016/j.psep.2011.06.022.

MacCarthy, B. L. *et al.* (2016) ‘Supply chain evolution – theory, concepts and science’, *International Journal of Operations and Production Management*, 36(12), pp. 1696–1718. doi: 10.1108/IJOPM-02-2016-0080.

Madadi, N. *et al.* (2013) 'Modeling and Simulation of a Bank Queuing System', in. IEEE, pp. 209–215. doi: 10.1109/CIMSim.2013.41.

Malinauskaite, J., Anguilano, L. and Rivera, X. S. (2021) 'Circular waste management of electric vehicle batteries: Legal and technical perspectives from the EU and the UK post Brexit', *International Journal of Thermofluids*, 10, p. 100078. doi: 10.1016/j.ijft.2021.100078.

Mason, R. and Lalwani, C. (2006) 'Transport integration tools for supply chain management', *International Journal of Logistics*, 9(1), pp. 57–74. doi: 10.1080/13675560500534599.

Masoumik, S. M. *et al.* (2014) 'Sustainable supply chain design: A configurational approach', *The Scientific World Journal*, 2014. doi: 10.1155/2014/897121.

Matopoulos, A., Barros, A. C. and van der Vorst, J. G. A. . (Jack) (2015) 'Resource-efficient supply chains : a research framework , literature review and research agenda', *Supply Chain Management*, 2(November 2014), pp. 218–236.

Matopoulos, A., Bell, J. E. and Aktas, E. (2016) 'The Use of Modelling in Purchasing/Supply Management Research', *Journal of Purchasing and Supply Management*, 22(4), pp. 262–265.

McKinnon, A. C. and Ge, Y. (2006) 'The potential for reducing empty running by trucks: a retrospective analysis', *International Journal of Physical Distribution & Logistics Management*, 36(5), pp. 391–410. Available at: https://doi.org/10.1108/09600030610676268.

Mehrjerdi, Y. Z. and Shafiee, M. (2021) 'A resilient and sustainable closed-loop supply chain using multiple sourcing and information sharing strategies', *Journal of Cleaner Production*, 289. doi: 10.1016/j.jclepro.2020.125141.

Mehta, R., Templeton, D. M. and Brien, P. J. O. (2006) 'Mitochondrial involvement in genetically determined transition metal toxicity', *Chemico-Biological Interactions*, 163, pp. 77–85. doi: 10.1016/j.cbi.2006.05.011.

Mena, C. *et al.* (2014) 'Causes of waste across multi-tier supply networks: Cases in the UK food sector', *International Journal of Production Economics*, 152, pp. 144–158. doi: 10.1016/j.ijpe.2014.03.012.

Miemczyk, J., Howard, M. and Johnsen, T. E. (2016) 'Dynamic development and execution of closed-loop supply chains: a natural resource-based view', *Supply Chain Management: An International Journal*, 21(4), pp. 453–469. doi: 10.1108/SCM-12-2014-0405.

Miles, M. B. and Huberman, A. M. (1994) *Qualitative data analysis : an expanded sourcebook.* 2nd ed. London: Sage. Available at: https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,url,shib,uid&db=cat00594a&AN=aston.b1076054&site=eds-live&authtype=ip,shib&custid=s9815128.

Mitchell, R. K. and Wood, D. J. (1997) 'Toward a theory of stakeholder identification and salience: Defining the principle of who and what really counts', *Academy of Management Review*, 22(4), pp. 853–886.

Moores, S. (2018) *Energy storage technologies: the supply chain risks and opportunities*. Oxford.

Morana, J. (2013) *Sustainable supply chain management*. ISTE (Automation-control and industrial engineering series). Available at: https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,url,shib,uid&db=cat

00594a&AN=aston.b2000889&site=eds-live&authtype=ip,shib&custid=s9815128.

Morecroft, J. D. W. (1984) ‘Strategy support models’, *Strategic Management Journal*, 5(3), pp. 215–229. doi: 10.1002/smj.4250050303.

Da Mota Pedrosa, A., Näslund, D. and Jasmand, C. (2016) ‘Logistics case study based research: towards higher quality’. doi: 10.1108/EL-01-2017-0019.

Narimissa, O., Kangarani-Farahani, A. and Molla-Alizadeh-Zavardehi, S. (2020) ‘Drivers and barriers for implementation and improvement of Sustainable Supply Chain Management’, *Sustainable Development*, 28(1), pp. 247–258. doi: 10.1002/sd.1998.

Nissan (2022) *XStorage*. Available at: https://www.nissan.ie/experience-nissan/electric-vehicle-leadership/xstorage-by-nissan.html (Accessed: 21 July 2022).

Nissan Insider (2016) *Second life LEAF batteries to power Amsterdam ArenA*. Available at: http://nissaninsider.co.uk/second-life-leaf-batteries-to-power-amsterdam-arena/.

OECD (2019) *Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences*. Paris.

Olsson, L. *et al.* (2018) ‘Circular business models for extended EV battery life’, *Batteries*, 4(4). doi: 10.3390/batteries4040057.

Pal, R., Sandberg, E. and Paras, M. K. (2019) ‘Multidimensional value creation through different reverse supply chain relationships in used clothing sector’, *Supply Chain Management*, 24(6), pp. 729–747. doi: 10.1108/SCM-12-2018-0422.

Patton, M. Q. (1990) *Qualitative evaluation and research methods, 2nd ed.* Thousand Oaks, CA, US: Sage Publications, Inc.

Pegden, D., Shannon, R. and Sadowski, R. (1995) *Introduction to simulation using Siman*. Second edi. Mc-Graw-Hill.

Pfeffer, J. (1981) *Power in organizations*. Pitman. Available at: https://search.ebscohost.com/login.aspx?direct=true&db=cat00594a&AN=aston.b1028726&site=eds-live&authtype=ip,shib&custid=s9815128.

Pfeffer, J. and Salancik, G. R. (1978) *The external control of organizations : a resource dependence perspective*. New York: Harper & Row. Available at: https://search.ebscohost.com/login.aspx?direct=true&db=cat00594a&AN=aston.b1004351&site=eds-live&authtype=ip,shib&custid=s9815128.

Phillips, L. (2007) ‘Decision conferencing’, in Cambridge University Press (ed.) *Advances in Decision Analysis: From Foundations to Applications*. New York, pp. 375–399.

Phillips, L. D. and Phillips, M. C. (1993) ‘Facilitated work groups: theory and practice’, *Journal of the Operational Research Society*, 44(6), pp. 533–549. doi: 10.1057/jors.1993.96.

Pidd, M. and Robinson, S. (2007) ‘Organising insights into simulation practice’, in *Proceedings of the 2007 Winter Simulation Conference*, pp. 771–775. doi: 10.1109/WSC.2007.4419672.

Ponsioen, T. C., Vieira, M. D. M. and Goedkoop, M. J. (2014) ‘Surplus cost as a life cycle impact indicator for fossil resource scarcity’, *International Journal of Life Cycle Assessment*, 19(4), pp. 872–881. doi: 10.1007/s11367-013-0676-z.

Potting, J. *et al.* (2017) *Circular Economy: Measuring innovation in the product chain*.

PwC. (2023). Electric Vehicle Sales Review Q1-2023. https://www.strategyand.pwc.com/de/en/industries/automotive/electric-vehicle-sales-review-2023-q1.html

Ramoni, M. O. and Zhang, H. C. (2013) 'End-of-life (EOL) issues and options for electric vehicle batteries', *Clean Technologies and Environmental Policy*, 15(6), pp. 881–891. doi: 10.1007/s10098-013-0588-4.

Randall, T. (2016) *Here's How Electric Cars Will Cause the Next Oil Crisis*. Available at: https://www.bloomberg.com/features/2016-ev-oil-crisis/ (Accessed: 12 July 2021).

Ravitch, S. M. and Riggan, J. M. (2016) *Reason and Rigor: How Conceptual Frameworks Guide Research*. Thousand Oaks:Sage Publications.

Reinhardt, R. *et al.* (2019) 'Towards sustainable business models for electric vehicle battery second use: A critical review', *Journal of Environmental Management*, 245(May), pp. 432–446. doi: 10.1016/j.jenvman.2019.05.095.

Renou, S. *et al.* (2008) 'Landfill leachate treatment : Review and opportunity', 150, pp. 468–493. doi: 10.1016/j.jhazmat.2007.09.077.

Reuters (2023) *Britain delays ban on new petrol and diesel cars to 2035, prime minister says*. Available at: https://www.reuters.com/world/uk/britain-delays-ban-new-petrol-diesel-cars-2035-pm-sunak-2023-09-20/.

Richa, K. *et al.* (2014) 'A future perspective on lithium-ion battery waste flows from electric vehicles', *Resources, Conservation and Recycling*, 83, pp. 63–76. doi: 10.1016/j.resconrec.2013.11.008.

Richardson, G. P. and Andersen, D. F. (1995) 'Teamwork in group model building', *System Dynamics Review*, pp. 113–137. doi: 10.1002/sdr.4260110203.

Richmond, B. (1997) 'The Strategic Forum: Aligning objectives, strategy and process', *System Dynamics Review*, 13(2), pp. 131–148. doi: 10.1002/(sici)1099-1727(199722)13:2<131::aid-sdr121>3.3.co;2-a.

Robinson, S. (2001) 'Soft with a hard centre: Discrete-event simulation in facilitation', *Journal of the Operational Research Society*, 52(8), pp. 905–915. doi: 10.1057/palgrave.jors.2601158.

Robinson, S. (2002) 'Modes of simulation practice : approaches to business and military simulation', *Simulation Modelling Practice and Theory*, 10(8), pp. 513–523. doi: 10.1016/S1569-190X(02)00117-X.

Robinson, S. *et al.* (2014) 'Facilitated modelling with discrete-event simulation: Reality or myth?', *European Journal of Operational Research*, 234(1), pp. 231–240. doi: 10.1016/j.ejor.2012.12.024.

Robinson, S. (2014) *Simulation: the practice of model development and use*.

Rockwell Automation (2020) *Arena Simulation Software*. Available at: https://www.arenasimulation.com/ (Accessed: 1 July 2020).

Rogers, D. S. and Tibben-lembke, R. (1999) 'Going backwards: reverse logistics trends and practices', in *Council of Logistics Management 1998 Annual Conference*.

Rohr, S. *et al.* (2017) 'A techno-economic analysis of end of life value chains for lithium-ion batteries from electric vehicles', *2017 12th International Conference on Ecological Vehicles and Renewable Energies, EVER 2017*. doi: 10.1109/EVER.2017.7935867.

Rosenhead, J. and Mingers, J. (2001) ‘A new paradigm of analysis’, in Wiley (ed.) *Rational Analysis for a Problematic World Revisited: Problem Structuring Methods for Complexity, Uncertainty, and Conflict*. Chichester, pp. 1–19.

Rossetti, M. (2015) *Simulation Modeling and Arena*. New York: John Wiley & Sons, Inc.

Rossman, G. B. and Wilson, B. L. (1985) ‘Numbers and Words: Combining Quantitative and Qualitative Methods in a Single Large-Scale Evaluation Study’, *Evaluation Review*, 9(5), pp. 627–643. doi: 10.1177/0193841X8500900505.

Roy, B. (1993) ‘Decision science or decision-aid science?’, *European Journal of Operational Research*, 66(2), pp. 184–203. doi: https://doi.org/10.1016/0377-2217(93)90312-B.

Russo, I., Pellathy, D. and Omar, A. (2020) ‘Managing Outsourced Reverse Supply Chain Operations: Middle-Range Theory Development’, *Journal of Supply Chain Management*, pp. 1–23. doi: 10.1111/jscm.12244.

Sanders, N. R. and Wagner, S. M. (2011) ‘Multidisciplinary and Multimethod Research for Addressing Contemporary Supply Chain Challenges.’, *Journal of Business Logistics*, 32(4), pp. 317–323. Available at: http://10.0.4.87/j.0000-0000.2011.01027.x.

Sanders, N. R., Zacharia, Z. G. and Fugate, B. S. (2013) ‘The Interdisciplinary Future of Supply Chain Management Research.’, *Decision Sciences*, 44(3), pp. 413–429. Available at: http://10.0.4.87/deci.12022.

Sarkis, J. (1995) ‘Manufacturing strategy and environmental consciousness’, *Technovation*, 15(2), pp. 79–97. doi: 10.1016/0166-4972(95)96612-W.

Sarkis, J., Zhu, Q. and Lai, K. H. (2011) ‘An organizational theoretic review of green supply chain management literature’, *International Journal of Production Economics*, 130(1), pp. 1–15. doi: 10.1016/j.ijpe.2010.11.010.

Saunders, M., Lewis, P. and Thornhill, A. (2016) *Research methods for business students. [electronic resource]*. Harlow, Essex : Pearson Education Limited, 2016. Available at: http://search.ebscohost.com/login.aspx?direct=true&AuthType=cookie,ip,url,athens,uid&db=cat00594a&AN=aston.b1669763&site=ehost-live.

Schein, E. H. (1998) *Process Consultation Revisited: Building the Helping Relationship*. 2nd ed. Addison-Wesley. Available at: https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,url,shib,uid&db=cat00594a&AN=aston.b1650351&site=eds-live&authtype=ip,shib&custid=s9815128.

Schenkel, M. *et al.* (2015) ‘Creating integral value for stakeholders in closed loop supply chains’, *Journal of Purchasing and Supply Management*, 21(3), pp. 155–166. doi: 10.1016/j.pursup.2015.04.003.

Schulz, M. *et al.* (2020) ‘Circular economy considerations in choices of LCA methodology: How to handle EV battery repurposing?’, *Procedia CIRP*, 90(March), pp. 182–186. doi: 10.1016/j.procir.2020.01.134.

Sebastiao, H. J. and Golicic, S. (2008) ‘Supply Chain Strategy for Nascent Firms in Emerging Technology Markets’, *Journal of Business Logistics*, 29(1), pp. 75–91. doi: 10.1002/j.2158-1592.2008.tb00069.x.

Seitz, M. A. and Wells, P. E. (2006) ‘Challenging the implementation of corporate sustainability: The case of automotive engine remanufacturing’, *Business Process Management Journal*, 12(6), pp. 822–836. doi: 10.1108/14637150610710954.

Sharfman, M. P., Shaft, T. M. and Anex, R. P. (2009) ‘The road to cooperative supply-chain environmental management: Trust and uncertainty among pro-active firms’, *Business Strategy and the Environment*, 18(1), pp. 1–13. doi: 10.1002/bse.580.

Simatupang, T., Wright, A. and Sridharan, R. (2002) ‘The knowledge of coordination for supply chain integration’, *Business Process Management Journal*, 8(3), pp. 289–308.

Simchi-Levi, D. (2014) ‘OM research: From problem-driven to data-driven research’, *Manufacturing and Service Operations Management*, 16(1), pp. 2–10. doi: 10.1287/msom.2013.0471.

Simio LLC (2020) *Simio Forward Thinking*. Available at: https://www.simio.com/ (Accessed: 1 July 2020).

Simon, H. A. (1967) ‘The Business School: A problem in organizational design’, *Journal of Management Studies*, 4(1), pp. 1–16. doi: 10.1111/j.1467-6486.1967.tb00569.x.

Smith, C. M. and Shaw, D. (2019) ‘The characteristics of problem structuring methods: A literature review’, *European Journal of Operational Research*, 274(2), pp. 403–416. doi: 10.1016/j.ejor.2018.05.003.

Smith, K. S. and Huyck, H. L. O. (1999) ‘An overview of the abundance, relative mobility, bioavailability, and human toxicity of metals’, *Reviews in Economic Geology*, 6, pp. 29–70. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-0002947822&partnerID=40&md5=0432bfb1c770bd832fc895b5ac42283d.

SNAM (2020) *Recycling*. Available at: http://www.snam.com/activites/recycling-snam.php (Accessed: 10 June 2020).

SNT (2022) *Spiers New Technologies*. Available at: https://www.spiersnewtechnologies.com/.

Sodhi, M. S. and Tang, C. S. (2014) ‘Guiding the next generation of doctoral students in operations management’, *International Journal of Production Economics*, 150, pp. 28–36. doi: 10.1016/j.ijpe.2013.11.016.

Sorker, F. (2008) *Investigation on Reverse Logistics of End of Life Cars in the UK*. Middlesex University.

Souza, G. C. (2018) *Sustainable operations and closed-loop supply chains*. Second edi. Business Expert Press (Supply and operations management collection). Available at: https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,url,shib,uid&db=cat00594a&AN=aston.b1966455&site=eds-live&authtype=ip,shib&custid=s9815128.

Spekman, R. E., Kamauff, J. W. and Myhr, N. (1998) ‘An empirical investigation into supply chain management: A perspective on partnerships’, *International Journal of Physical Distribution & Logistics Management*, 28(8), pp. 630–650. doi: 10.1108/13598549810215379.

Srivastava, S. K. (2007) ‘Green supply-chain management: A state-of-the-art literature review’, *International Journal of Management Reviews*, 9(1), pp. 53–80. doi: 10.1111/j.1468-2370.2007.00202.x.

Standridge, C. R. and Hasan, M. (2015) ‘Post-Vehicle-Application Lithium – Ion Battery Remanufacturing , Repurposing and Recycling Capacity : Modeling and Analysis’, 8(3), pp. 823–839.

Stuart, I. *et al.* (2002) ‘Effective case research in operations management : a process perspective’, *Journal of Operations Management*, (20), pp. 419–433.

Sudusinghe, J. I. and Seuring, S. (2022) ‘Supply chain collaboration and sustainability performance in circular economy: A systematic literature review’, *International Journal of Production Economics*, 245(December 2021), p. 108402. doi: 10.1016/j.ijpe.2021.108402.

Swain, B. (2017) ‘Recovery and recycling of lithium: A review’, *Separation and Purification Technology*, 172, pp. 388–403. doi: 10.1016/j.seppur.2016.08.031.

Tako, A. A., Kotiadis, K. and Vasilakis, C. (2010) ‘A participative modelling framework for developing conceptual models in healthcare simulation studies’, *Proceedings - Winter Simulation Conference*, (June 2014), pp. 500–512. doi: 10.1109/WSC.2010.5679135.

Tako, A. A. and Robinson, S. (2010) ‘Model development in discrete-event simulation and system dynamics: An empirical study of expert modellers’, *European Journal of Operational Research*, 207(2), pp. 784–794. doi: 10.1016/j.ejor.2010.05.011.

Tchounwou, P. B. *et al.* (2012) ‘Heavy Metal Toxicity and the Environment’, in Luch, A. (ed.) *Molecular, Clinical and Environmental Toxicology*. Basel: Springer Basel, pp. 133–164. doi: 10.1007/978-3-7643-8340-4_6.

Teece, D. J., Pisano, G. and Shuen, A. (1997) ‘Dynamic capabilities and strategic management’, *Knowledge and Strategy*, 18(7), pp. 509–533. doi: 10.1093/0199248540.003.0013.

Touboulic, A. and Walker, H. (2011) ‘Theories in sustainable supply chain management : a structured literature review’. doi: 10.1108/IJPDLM-05-2013-0106.

Toyota (2019) *Hybrid HV Battery Recycling Program*. Available at: https://www.toyota.com.au/hybrid/battery-recycling.

Umicore (2020a) *Battery recycling: Audi and Umicore start closed loop for cobalt and nickel*. Available at: https://www.umicore.com/en/media/press/battery-recycling-audi-and-umicore-start-closed-loop-for-cobalt-and-nickel/ (Accessed: 10 June 2020).

Umicore (2020b) *Battery Recycling*. Available at: https://csm.umicore.com/en/recycling/battery-recycling/ (Accessed: 10 June 2020).

USDOC (2012) *Sustainable Manufacturing, U.S. Department of Commerce*. Available at: http://www.trade.gov/competitiveness/sustainablemanufacturing/how_doc_defines_SM.asp (Accessed: 31 March 2022).

Vachon, S. and Klassen, R. D. (2006) ‘Green project partnership in the supply chain: The case of the package printing industry’, *Journal of Cleaner Production*, 14(6–7), pp. 661–671. doi: 10.1016/j.jclepro.2005.07.014.

Van de Ven, A. H. (1989) ‘Nothing Is Quite So Practical as a Good Theory’, *Academy of Management Review*, 14(4), pp. 486–489. doi: 10.5465/amr.1989.4308370.

Vennix, J. (1996) *Group Model Building: Facilitating Team Learning using System Dynamics*. Chichester: Wiley.

Vlachos, D., Georgiadis, P. and Iakovou, E. (2007) ‘A system dynamics model for dynamic capacity planning of remanufacturing in closed-loop supply chains’, 34, pp. 367–394. doi: 10.1016/j.cor.2005.03.005.

Volkswagen (2019) *Lithium to lithium, manganese to manganese*. Available at: https://www.volkswagenag.com/en/news/stories/2019/02/lithium-to-lithium-manganese-to-manganese.html.

Voss, C., Tsikriktsis, N. and Frohlich, M. (2002) 'Case research in operations management', *International Journal of Operations and Production Management*, 22(2), pp. 195–219.

Walker, H. *et al.* (2012) 'Sustainable procurement: Past, present and future', *Journal of Purchasing and Supply Management*, 18(4), pp. 201–206. doi: 10.1016/j.pursup.2012.11.003.

Wang, F., Lai, X. and Shi, N. (2011) 'A multi-objective optimization for green supply chain network design', *Decision Support Systems*, 51(2), pp. 262–269. doi: 10.1016/j.dss.2010.11.020.

Waters, C. D. J. and Rinsler, S. (2014) *Global logistics : new directions in supply chain management.* London, United Kingdom ; Philadelphia, PA, USA : Kogan Page, 2014. Available at: http://search.ebscohost.com/login.aspx?direct=true&db=cat00594a&AN=aston.b1752226&site=eds-live&authtype=ip,shib&custid=s9815128.

Williams, T. (2008) *NoManagement science in practice*. Chichester: Wiley.

Winslow, K. M., Laux, S. J. and Townsend, T. G. (2018) 'A review on the growing concern and potential management strategies of waste lithium-ion batteries', *Resources, Conservation and Recycling*, 129(October 2017), pp. 263–277. doi: 10.1016/j.resconrec.2017.11.001.

WMG (2020) *Automotive Lithium ion Battery Recycling in the UK*, *Report Summary:2020*. Coventry.

Wong, C. W. Y. *et al.* (2012) 'Green operations and the moderating role of environmental management capability of suppliers on manufacturing firm performance', *International Journal of Production Economics*, 140(1), pp. 283–294. doi: 10.1016/j.ijpe.2011.08.031.

Woodside, A. G. and Wilson, E. J. (2003) 'Case study research methods for theory building', *Journal of Business and Industrial Marketing*, 18(6–7), pp. 493–508. doi: 10.1108/08858620310492374.

Wu, I. L., Chuang, C. H. and Hsu, C. H. (2014) 'Information sharing and collaborative behaviors in enabling supply chain performance: A social exchange perspective', *International Journal of Production Economics*, 148, pp. 122–132. doi: 10.1016/j.ijpe.2013.09.016.

Yanikara, F. S. and Kuhl, M. E. (2015) 'A simulation framework for the comparison of reverse logistic network configurations', *Proceedings - Winter Simulation Conference*. doi: 10.1017/CBO9781107415324.004.

Yin, R. K. (2009) *Case study research : design and methods.* Los Angeles : Sage Publications, ©2009. (Applied social research methods series: v.5). Available at: http://search.ebscohost.com/login.aspx?direct=true&db=cat00594a&AN=aston.b1297198&site=eds-live&authtype=ip,shib&custid=s9815128.

Yu, M., Bai, B. and Ma, X. (2021) 'Evaluating Remanufacturing Lithium-Ion Batteries', *Wastewater Technologies and Environmental treatment*, (January). doi: 10.1007/978-3-030-61989-3.

Zeng, X., Li, J. and Liu, L. (2015) 'Solving spent lithium-ion battery problems in China: Opportunities and challenges', *Renewable and Sustainable Energy Reviews*. doi: 10.1016/j.rser.2015.08.014.

Zhao, J., Liu, W. and Wei, J. (2013) 'Pricing and remanufacturing decisions of a decentralized fuzzy supply chain', *Discrete Dynamics in Nature and Society*, 2013. doi: 10.1155/2013/986704.

Zhu, J. *et al.* (2021) 'Perspective End-of-life or second-life options for retired electric vehicle batteries', *Cell Reports Physical Science*, 2(8), p. 100537. doi: 10.1016/j.xcrp.2021.100537.

Zimmer, K., Fröhling, M. and Schultmann, F. (2016) 'Sustainable supplier management - A review of models supporting sustainable supplier selection, monitoring and development', *International Journal of Production Research*, 54(5), pp. 1412–1442. doi: 10.1080/00207543.2015.1079340.

Zobel, A. K. (2017) 'Benefiting from Open Innovation: A Multidimensional Model of Absorptive Capacity*', *Journal of Product Innovation Management*, 34(3), pp. 269–288. doi: 10.1111/jpim.12361.