Developing the Electric Vehicle Battery Recycling Supply Chain

"A Case Study in Using Packaging as a Competitive Advantage"

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Acknowledgements

This master's thesis represents the culmination of our Master of Science degree in Industrial Engineering and Management, marking the end of our five-year journey at Lund University. Throughout our degree program, we have acquired a valuable set of skills, competencies, and knowledge that have equipped us for the transition into the professional world. Working with this thesis has given us the opportunity to explore our interests in the intersection of supply chain management, strategy, and technology.

We would like to express our sincere gratitude to our supervisor, Eva Berg, for her support, belief in our competencies, and invaluable feedback throughout the process of writing this thesis. Additionally, we extend our thanks to our examiner, Dag Näslund, for his expertise and thought-provoking questions.

We would also like to take the opportunity to extend an especially warm thank you to our case company supervisor. You have supported us throughout this process and have always been available for questions and guidance. Also, we would like to extend our warmest thank you to the interviewees who shared their time and provided us with extensive insights. Your participation and willingness to answer our questions have had a large impact on the thesis result and our personal learning trajectory. This thesis would not have been possible without your valuable contributions.

Lastly, we would like to express our deepest appreciation to our families and friends for their unwavering support and encouragement during these five years. Their constant presence and belief in our abilities have been instrumental throughout our academic journey.

Lund, May 2023

Abstract

The demand for electric vehicles (EVs) and battery production necessitates efficient logistics for battery recycling. However, the industry currently lacks widely adopted packaging and logistics standards, resulting in efficiency losses. Existing solutions are often expensive and overly safe for most recycled batteries. Additionally, limited research on large-scale EV battery recycling has been published. Therefore, there is a need to explore the benefits, design, and conditions for a battery recycler to provide a unified packaging and logistics solution.

This thesis investigates the benefits of implementing a unified packaging and logistics solution for battery recycling. A single case study is conducted, interviewing representatives from an organization involved in battery recycling. External interviews with industry experts are also conducted, and relevant literature reviewed.

The analysis revolves around mapping different battery flows that a unified packaging system would handle. Five packaging design alternatives are presented, and their operational performance examined. The financial performance of each design alternative is evaluated, considering costs and comparing them to the current operations of the case company.

The findings show that implementing a unified packaging solution aligned with the recycler's business strategy can lead to significant cost savings and increased willingness to pay from original equipment manufacturers (OEMs). The thesis provides battery recyclers with a comprehensive list of requirements for packaging solutions in European OEM flows, and an evaluation model for comparing different design alternatives. Future research could explore combining multiple packaging solutions to create a portfolio and bringing recycling process steps closer to the OEMs, reducing the complexity of packaging needs.

Contribution: This thesis has been a complete elaboration between the two authors.
Each author has been involved in every part of the process and contributed equally.

Keywords: Battery Recycling, Electric Vehicle Batteries, Supply Chain Management, Packaging Development

Sammanfattning

Efterfrågan på elbilar (EVs) och batteriproduktion kräver effektiv logistik för batteriåtervinning. Branschen lider dock för närvarande av bristande antagande av standarder för förpackning och logistik, vilket leder till effektivitetsförluster. Befintliga lösningar är ofta dyra och överdrivet säkra för de flesta återvunna batterier. Dessutom har begränsad forskning om storskalig återvinning av EV-batterier publicerats. Det finns därför ett behov av att utforska fördelarna, designen och förutsättningarna för att en batteriåtervinnare ska kunna erbjuda en enhetlig förpacknings- och logistiklösning.

Detta examensarbete undersöker fördelarna med att implementera en enhetlig förpacknings- och logistiklösning för batteriåtervinning. En fallstudie genomförs, där representanter från en organisation som är involverad i batteriåtervinning intervjuas. Externa intervjuer med branschexperter genomförs också, och relevant litteratur granskas.

Analysen fokuserar på att kartlägga olika batteriflöden som en enhetlig förpackningssystem skulle hantera. Fem förpackningsdesignalternativ presenteras, och deras operationella prestanda undersöks. Den ekonomiska prestandan för varje designalternativ utvärderas med avseende på kostnader och jämförs med den nuvarande verksamheten hos fallföretaget.

Resultaten visar att implementeringen av en enhetlig förpackningslösning som är i linje med återvinnarens affärsstrategi kan leda till betydande kostnadsbesparingar och ökad betalningsvilja från ursprungliga utrustningstillverkare (OEM). Avhandlingen ger batteriåtervinnare en omfattande lista över krav för förpackningslösningar i europeiska OEM-flöden och en utvärderingsmodell för att jämföra olika designalternativ. Framtida forskning kan utforska möjligheten att kombinera flera förpackningslösningar för att skapa en portfölj och föra återvinningsprocesssteg närmare OEM:er, vilket minskar komplexiteten i förpackningsbehoven.

Bidrag: Detta examensarbete är resultatet av ett samarbete mellan författarna. Båda författarna har varit med i alla delar i processen och bidragit till lika delar.

Nyckelord: Batteriåtervinning, Elbilsbatterier, Supply Chain Management, Förpackningsutveckling

Table of Content

List of Figures

List of Tables

Abbreviations

ADR: Agreement of 30 September 1957 concerning the International Carriage of Dangerous Goods by Road

BEV: Battery Electric Vehicle

CAGR: Compounded Annual Growth Rate

EOL: End of Life

EV: Electric Vehicle

EVB: Electrical Vehicle Battery

FTL: Full Truck Load

OEM: Original Equipment Manufacturer

PHEV: Plug-in Hybrid Electric Vehicle

SOH: State of Health

1. Introduction

The introduction chapter presents the thesis background, describes the problem analyzed, and the purpose of this research study. It also gives an introduction to the research question and objectives that will be addressed. As a final part, the focus and delimitation are presented before providing the structure of the thesis.

1.1 Background

With regards to the severity of the ongoing climate crisis, many industries are changing to become more sustainable and fit for future challenges (World Economic Forum, 2020; World Meteorological Organization, 2017). This change can be seen in industries such as textile, food, consumer electronics, and maybe even more prominently in the automotive industry. Actors in the industry are driven not only by an increasing customer demand for sustainable solutions and products, but also by regulatory initiatives to reduce GHG emissions. One of the most influential changes in the industry is the EU regulation *Fit for 55*, initiating a 55% cut of the emissions from newly produced cars by 2030, and a 100% cut of emissions by 2035 (European Council, 2021). This has led the original equipment manufacturers (OEMs) to rush their development and production of electric vehicles (EVs), and the future projection of sold EVs in the EU has skyrocketed (BloombergNEF, 2022). One estimate of the growing demand suggests a tenfold growth from 2020 to 2030 and Morgan Stanley projects a 95% market penetration by EVs in 2035 - if supply can keep up (Blue Institute, 2022; Morgan Stanley, et al, 2021).

To manage the supply side of the market equation, OEMs need to secure the sourcing, production, distribution, and recycling of EV batteries. This supply cycle is becoming increasingly dominant in the automotive industry and OEMs are spending billions on the development and refining of efficient solutions (Reuters, 2022). Supply chain development does not only need to be rapid, but it also must be environmentally, socially, and economically sustainable. A highlighting example of this is the scarcity of traditional metals used in battery production (usually lithium, cobalt, manganese, aluminum, and nickel). These metals are in high demand and the industry is risking a worldwide shortage of these components as soon as 2025 (IEA, 2021). Therefore, both industry and academia are developing recycling strategies and methods for old batteries to bridge the gap in supply. To connect supply with end of life (EOL) products is often referred to as "closing the loop" and is a hot topic when it comes to making industries and their production flows more sustainable (Northvolt, 2019). The recycling and disposal of electric vehicle batteries (EVB) is one of the main challenges facing the EV market (Kuemmerle et al., 2021).

Closing the loop for the EV batteries has however proven to be a difficult task and there are, as of April 2023, no large-scale circular operation models in Europe (BloombergNEF, 2022). The reason for this is mainly that the EV market is still in its early stages and that a design standard is yet to fully be established (McKinsey, 2018). Immature markets are prone to instability, swift changes, and radical innovation, making it increasingly difficult to establish sustainable long-term solutions that focus on making the supply chain more circular (Abernathy and Utterback, 1978; Hopkinson et al., 2019). There's also an academic demand for further research on the concept of circular economy in the automotive industry (Slattery et al., 2021). Because of this and the need to capture market shares, it can appear logical to first establish sufficient production to meet demand, and only when this is in place, manage EOL products, sustainability aspects and other more long-term issues. However, this approach will not be viable for the current situation, which urgently demands rapid and sustainable change.

1.2 Problem Description

With the expected increase in EV demand and production of batteries, and the enhanced need for battery recycling, it is vital that the enabling logistics run smoothly. Today there is no widespread packaging and logistics standard for recycled batteries, resulting in an overall handling difficulty and efficiency loss. Additionally, of the few solutions available the majority are expensive and do in many cases have safety features that are excessive for handling most of the batteries used in recycling. It is only a small fraction of the recycled batteries that have the need for such safety. Further, large scale EVB production and recycling is still novel, and researchers have yet to fill the research gap in the field of logistics related to these batteries. Given this background, there is a need and interest to explore whether it would be beneficial for a battery recycler to offer a unified packaging and logistics solution for battery recycling, how it would be designed, and under what conditions.

1.3 Purpose and Research Question

The purpose of this thesis is to investigate how a battery recycler can benefit from offering a unified packaging- and logistics solution for battery recycling, what a solution could look like, and how supply chain performance will be affected by such a solution.

Originating from the purpose of this thesis, the main research question to be answered concerns the logistics setup for a standardized packaging solution for batteries used for recycling, and how a battery recycler can benefit from developing their logistics service offering. The question is formulated as follows:

RQ1. How can a battery recycler benefit from offering a unified packaging- and logistics solution for battery recycling?

To answer this question, an extensive analysis of a recycler's operations and supply chain is required, focusing on understanding the affected flows and how these can be improved by implementing a standardized packaging solution. The analysis includes components such as process mapping, packaging requirements, an overview of the packaging life cycle, and financial modeling of proposed change initiatives. These aspects are all aimed to clarify if and how a standardized packaging and logistics setup can be seen as a benefit, and potentially a unique selling point, for battery recyclers. This analysis strives to answer the following research objective:

RO1. Map the resources and conditions needed to support a standardized packaging and logistics solution.

To complement RO1, an exhaustive mapping of factors limiting the solution is required to validate this thesis and cement its relevance. Understanding the regulatory and commercial environment where the battery recycler operates is crucial for future implementation of the conclusions presented in this thesis. Without a solid connection to current limitations, the thesis risks losing its relevance. Limiting aspects included are regulatory, financial, and operational. Together they answer the following research objective:

RO2. Map regulatory, financial, and operational aspects limiting the solution.

Together, RO1 and RO2 identify the enablers and limitations that define the solution space for viable supply chain designs. By combining them, possible supply chain setups can be designed and evaluated. This is addressed in RO3:

RO3. Suggest a viable supply chain setup in the mapped solution space.

By suggesting a viable supply chain setup, the concept of a standardized logistics solution for battery recyclers can be evaluated, and benefits can be weighed against potential drawbacks. To evaluate actual solutions, five design alternatives will be developed and given different characteristics and qualities. These will then be examined and compared to each other, evaluating their viability as future packaging- and logistic solutions. With this evaluation, the main question will be answered.

1.4 Focus and Delimitation

The thesis will take a holistic approach analyzing and solving logistics problems connected to the standardization of packaging. However, due to time restrictions the scope must be limited, and delimitations must be specified. This section presents te focus and delimitations of the report.

The following list summarizes the focus areas of the thesis, which then are further elaborated on:

- Packaging solution for transport of EOL, recall and scrap lithium-ion batteries (LIB) to a battery recycler from OEMs
- Batteries classified as green and yellow
- Road transportation in Europe

- Time frame of approximately 10 years

The following points are out of scope:

- The material sourcing, production, usage, and recycling of EVBs

The products in focus are EOL, recall and scrap lithium-ion batteries (LIB) from OEMs that are classified as green and yellow. Batteries are classified according to an industry standard where green and yellow batteries are less damaged than red batteries and hence require less strict safety precautions when transported. The study, which is also limited to road transport in Europe, focuses on these safety classifications because they stand for most recycled batteries on the European market (stated in an interview with the case company). Further, the battery type in focus for the thesis is EVBs. This is because most lithium-ion batteries (LIB) are found in EVs as well as the market's expected growth *(World Economic Forum, 2019).*

Finally, the thesis will focus on the long-term viability for the presented case settings and suggested solutions. The long-term focus is a result of two factors inherent in the situation. First, EVBs have a lifetime of 10 to 15 years in use, which is expected to increase with future technological advances (Gruber et al., 2011; Kempton & Tomic, 2009; Kalhammer et al., 2008). This prolongs the life cycle of any used EVB, and hence the solution horizon on the packaging solution supporting it. Second, the source of battery flow is likely to shift over time. Today most EVBs are recycled prematurely (e.g., accident or testing), while the future flows most likely will come from EOL batteries. Therefore, a fixed standardized solution designed for the current flows will be obsolete soon. A sustainable setup, consequently, must have a longer time perspective. These two factors together force any attempt at standardization to adopt a time horizon fitting to the lifetime of an EVB.

1.5 Structure of Thesis

The thesis is structured around seven main chapters: *1. Introduction*, *2. Literature Review*, *3. Methodology*, *4. Empirics*, *5. Analysis*, *6. Evaluation*, and *7. Conclusion*. These chapters follow the problem-solving structure of the thesis where the background and problem first is formulated, then a theoretical framework is presented, followed by a description of how this framework together with the case study will answer the research question. After presenting the methodology, the empirics account for the collected data and make up the building blocks that together with the literature review is set to answer the research question. This is followed by an analysis and creation of different packaging design alternatives. When alternatives have been created, they are then evaluated and compared to each other. The thesis is then finalized by a conclusion and an answered research question.

The connection between the problem-solving structure, the chapters of the thesis, as well as the output of each step, is illustrated in *Figure 1.1*. Each chapter will now be described in more detail.

Chapter	Focus of Thesis		Output
1	Background	→	Research objectives and questions
2	Literature Review	→	Theoretical framework
3	Methodology	→	Design of thesis and problem solving approach
4	Empirics	→	Findings from the case study, supported by external findings
5	Analysis	→	Possible solutions for the research question
6	Evaluation	→	Performance evaluation for each design alternative
7	Conclusion	→	Answer research question and further research areas

Figure 1.1. An illustration of the connection between the problem-solving structure, the chapters of the thesis, and the main output of each section. (Source: own illustration)

In chapter ***2. Literature Review*** the theoretical framework of the thesis is presented and relevant theory is explained. The purpose of this chapter is to provide the reader with theory supporting the understanding of the thesis. This chapter presents the theoretical findings relating to the research question, the methodology, and frameworks used. To cover these areas, the chapter is divided into one section focusing on the EV battery, one for the supply chain theory, and one relating to the packaging logistics.

Chapter ***3. Methodology*** presents the approach taken to answer the research question. The methodology focuses on the choice of research strategy, methodology, and method. Further, it also presents the research design and the selected unit of analysis. This is followed by a section on data collection and how it is conducted. In addition, the chapter also presents the general idea and approach of the data analysis, as well as an exposition of the research quality.

In chapter ***4. Empirics*** the main results from the data collection are presented and explained. The chapter is commenced by a section covering the product characteristics, focusing on what qualities unite or separates different batteries. Second, a mapping of the processes and product flows is presented. The purpose of this section is to account for the relevant processes affecting the EVB and its packaging solution, as well as presenting the expected market size of the recycling market. Further, an exposition of the resulting packaging requirements is presented, also connecting requirements to different stakeholders involved in the processes. Finally, the chapter presents findings on the EVB recycling market, the stakeholders involved, how the future growth can be estimated and how it will be affected by general trends.

Chapter ***5. Analysis*** takes the results, combines it with the theoretical findings and frameworks, and aims to analyze this data to find possible answers for the research question. First, an analysis of the current and future flow is presented, followed by product categorization. These parts are followed by the creation of viable design alternatives for different possible solutions. An evaluation model addressing the financial aspects of the supply chain setup is also presented together with each design alternatives financial performance.

In chapter ***6. Evaluation***, the scenarios are evaluated by comparing their performance and evaluating the sensitivity of the model and performance. In addition to the financial evaluation, this chapter also evaluates qualitative aspects of the proposed solutions, as well as their strategic implications. The chapter ultimately aims to compare the design alternatives and to connect them to a given supply chain strategy.

Finally, chapter ***7. Conclusion*** will conclude the thesis, summarizing the findings, and present an answer to the research question. Additionally, further research areas and questions will be presented to inspire further studies of similar and adjacent areas. This will be the finalizing part of the thesis, followed by references and an appendix.

2. Literature Review

This chapter covers relevant theories and literature findings on topics connected to the thesis. Found when researching the subject, is that there is a lack of literature covering the cross section between EVB recycling, supply chain theory, and packaging logistics. Therefore, the literature research has been divided into subparts, covering the mentioned areas respectively to help build a fundamental understanding for the topic. The learnings are then combined in the result and analysis phase of this thesis, contributing to academia by connecting the three fields.

2.1 EV Batteries

This section focuses on the attributes and characteristics of EV batteries. Further it provides an outline for the EVB life cycle and its different phases. Finally, it accounts for the regulatory restrictions applied to EVBs when they are transported.

2.1.1 EV Battery Life Cycle

The market for EVBs is still emerging and continuously subject to major change (Rajaeifar et al., 2021). This leads to variability in battery compositions, market sizes, battery applications, logistical solutions, and other areas. However, by studying different process flow descriptions, five main stages of the EVB life cycle emerge which are described in the following sections, and illustrated in *Figure 2.1* (Hendrickson et al., 2017; Xia & Li, 2020; Nurdiawati & Agrawal, 2021; Yang, Huang & Lin, 2019).

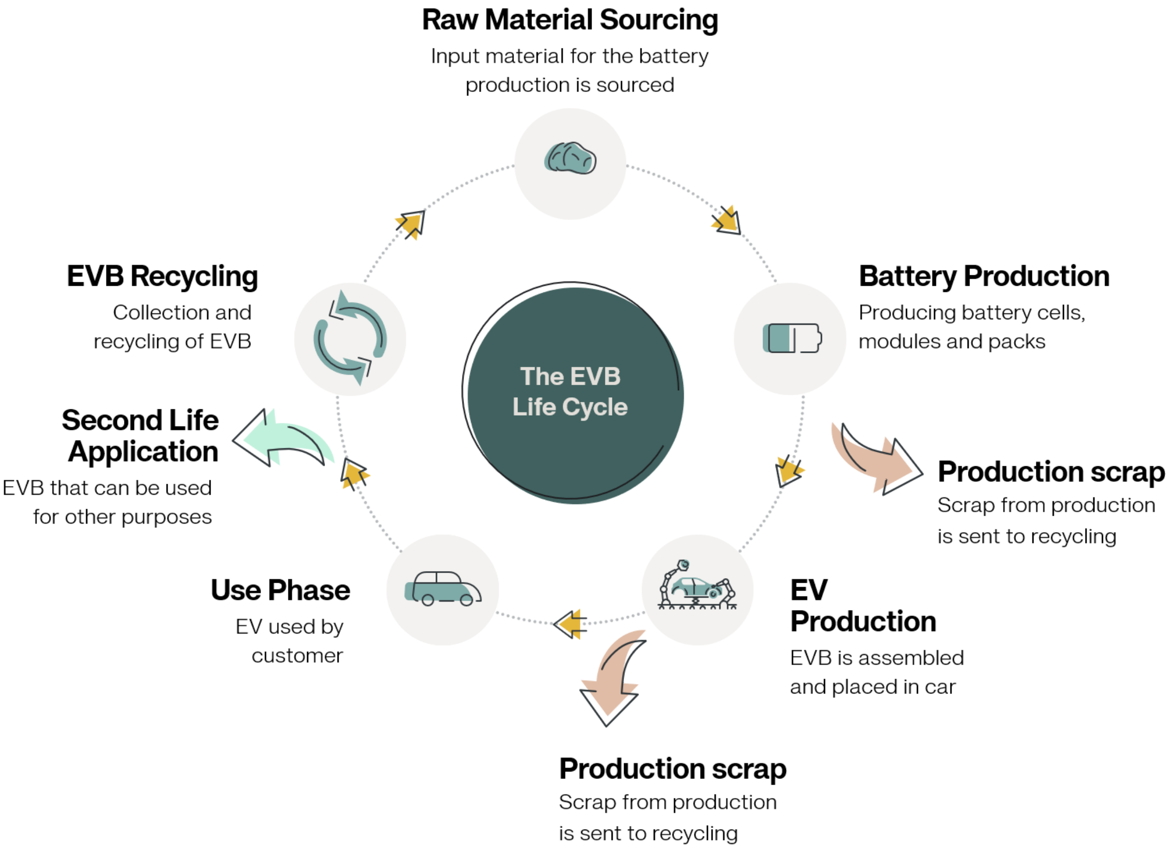


Figure 2.1. An illustrative map of the EVB life cycle (Hendrickson et al., 2017; Xia & Li, 2020; Nurdiawati & Agrawal, 2021; Yang, Huang & Lin, 2019). (Source: own illustration)

First, the material must be sourced and procured. The particularly critical part of this step is to successfully source the scarce metals used when producing battery cells. For EVBs, the most used metals are lithium, cobalt, manganese, aluminum and nickel, all subject to supply risk (*Nurdiawati & Agrawal, 2021*). For example, the IEA points out that the world could face lithium shortages in 2025 (IEA, 2021) if sufficient investments are not made to expand production. As of today, estimates suggest that 5% of the world's lithium-ion batteries are recycled, however due to material scarcity, the trend within the industry is to move towards using a higher rate of recycled metals in production (CAS Insights, n.d.). Closed-loop systems with recycling at EOL have recently gained more attention since they provide a way to lower environmental impacts and gain access to high value material to be used in new batteries (Mayyas, Steward & Mann, 2020).

Second, when the raw material and components are sourced the following phase is production. The production of a battery can exhaustively be detailed, however it is not relevant for the purpose of this thesis. In contrast, what is of interest are the three main levels of an EV battery: cell, module and pack illustrated in *Figure 2.2* (Horowitz & Coffin, 2019). Starting with the cell, it is the smallest component consisting of a separated cathode and anode, connected electrically by an electrolyte. This composition can be built from different materials, but the two most common compositions for EVs are NMC (nickel, manganese, and cobalt) and NCA (nickel cobalt aluminum oxides) LIBs. Cells are produced as an intermediate good to be assembled into larger modules and packs, but they approximately make up 75% of the total cost for an average battery pack. Today, the large majority (79%) of LIBs are produced in China, but the European market share is expected to grow, mainly from Germany (Statista, 2021).

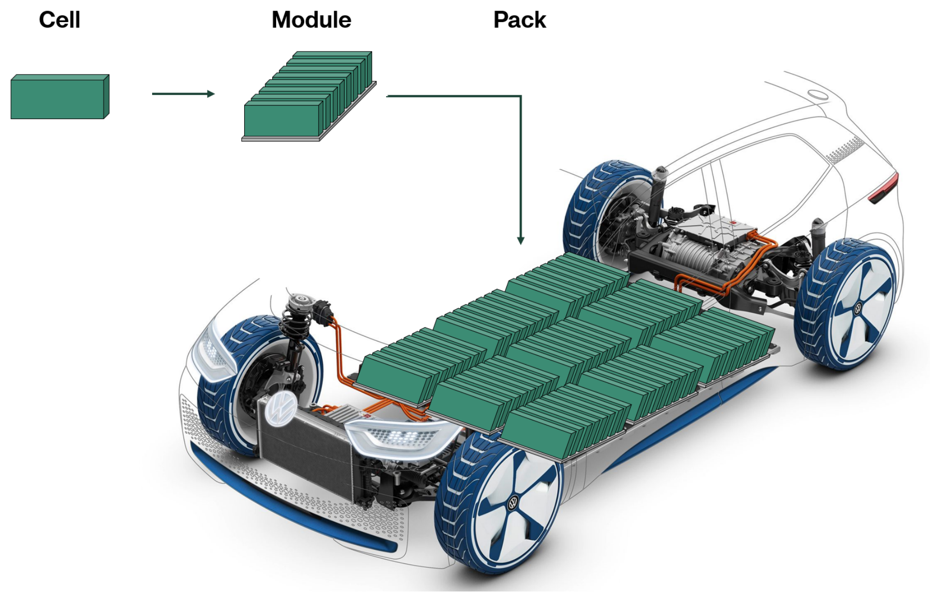


Figure 2.2. Illustration of the battery hierarchy in an EV. (Source: own illustration)

The next level of an EVB is a module, uniting multiple cells electrically connected that are contained by a protecting frame (Zwicker et al., 2020). There are no standards in the number of cells used in a module, or how to connect them, giving the car manufacturers the freedom to design their modules as preferred to reach the desired performance. When the modules are designed and assembled, they are put into a pack, the last level of an EVB. Packs are seen as the final stage and connect several modules in one unit. Packs are usually designed for specific vehicle models and can differ in performance, size, lifetime, and other aspects. This variation can arguably make later steps in the battery's life cycle more complex.

Third, the battery pack is put into a car or sent to a testing facility by the OEM. This is considered the use-phase of the battery and can take different forms. Sources of battery flows from OEMs for recycling are usually related to battery testing, scrap recovery from production, recycling of material from crashed cars, or EOL vehicles.

Lastly, reconnecting to *Figure 2.1*, when the EVB has served its purpose and the residual capacity is considered insufficient for automotive use, it reaches its end of life. A common measure is that batteries for EV application reach their end of life when they reach approximately 80% of the original capacity, also referred to as State of Health (SOH) (Canals Casals, Amante García & Canal, 2017; Williams & Lipman, 2012). Several factors that affect the lifespan vary for each battery, such as driving conditions and overcharging, and therefore it is difficult to give an exact number for how long the EVB is fit. Therefore, different researchers provide numbers ranging from 5-15 years (Gruber et al., 2011; Marano et al., 2013; Kalhammer et al., 2008). When reaching this SOH level, batteries may be considered for recycling, however an increasing interest for these batteries are coming from reuse applications. This is called a second life application where the EVB is used for another purpose, for example in the energy grid or in a vehicle requiring less power (Canals Casals, Amante García & Canal, 2017).

When recycling an EVB it undergoes four major steps to retrieve the four main metals (Northvolt, n.d.; Hendrickson et al., 2017). The initial step is to discharge and short circuit the battery to reduce the danger of handling it. This is performed due to safety reasons and can either be done by emptying the charged battery electrically into the local power grid, or chemically by using a salt bath (Nembhard, 2021). The second step is dismantling, which can either be done manually or automatically. Regardless of process, the purpose of this step is to separate the cells from its protecting modules and pack. When dismantled, the remaining parts are crushed into a powder called black mass from which a sorting process can separate the different materials. These are then later inserted in the material recovery phase from which pure metals can be extracted to later be used in the production of new batteries. Today, there are companies recovering up to 95% of the materials using these recycling processes (Northvolt, n.d.).

There are environmental as well as economic and geopolitical reasons to recycle EVBs when reaching EOL. From an environmental perspective, recycling of EVBs has the potential to significantly reduce the emissions associated with the production (World Economic Forum, 2019), with as much as up to 70% (Mayyas, Steward & Mann, 2020). Economically, an increasing rate of recycled material in EVBs is motivated by the fact that resources that are critical to the battery are finite and subject to a potential supply risk. At the same time, the increasing electrification trend in society threatens to further worsen the supply situation (Shine, I., 2022). The supply concern is further deepened since 60% of the found lithium reserves are found in drought-prone locations which is problematic for the water intensive mining and extraction process. Another economic argument is the fact that the EVB makes up to 30-50% of the cost of the vehicle, which is why recycling is attractive instead of extracting new material (Melin, H. E., 2019). While geopolitically, the trend towards developing European recycling of LIBs is a result of the continent’s low influence in the supply chain. The leading actors throughout the supply chain are all located in Southeast Asia with China as the leader, largely due to the experience from production and recycling of consumer electronics (Mayyas, Steward & Mann, 2020; Drabik & Rizos, 2018). This causes an imbalance of market power that results in European dependency on foreign countries for import of critical input materials to the EV production (Drabik & Rizos, 2018).

2.1.2 Regulations for Battery Waste Transportation

Besides being bulky and heavy, EVBs are considered as dangerous goods associated with the risk of fire, release of toxic gasses and liquids but also electric chocks that could potentially be fatal (Economic Commission for Europe Inland Transport Committee, 2021). Because of this risk, an industry standard has been developed categorizing batteries as green, yellow, or red depending on their condition (NEFAB, 2020). Green batteries are not damaged and allowed to be transported under normal conditions, whereas yellow batteries are damaged which is why tougher packaging requirements apply. Yellow batteries are also banned from air transport. The red batteries are defined as "liable to rapidly disassemble, dangerously react, produce a flame or a dangerous evolution of heat or a dangerous emission of toxic, corrosive or flammable gasses or vapors under normal conditions of carriage" (Economic Commission for Europe Inland Transport Committee, 2021a). As stated in *1.4 Focus and Delimitation*, red batteries are more regulated when transported and more unusual on the market and are therefore considered out of scope for this thesis.

To prevent any accident, nations have agreed to the UN treaty ADR that regulates the transport of dangerous goods. These regulations require transporters of EVBs to take further safety measures which imply additional costs to the battery recycling process (Stallery, 2021). Among other things, ADR includes definitions of hazardous waste classes and guidelines for how to package them appropriately during transport (Economic Commission for Europe Inland Transport Committee, 2021). The section in ADR that regulates transport of damaged LIBs is called Special Provision 376. For a battery to be classified as damaged, a condition assessment must be carried out by a technical expert who can identify batteries that, for example have an electrolyte leakage or sustained physical damage. These batteries are considered defective and to ensure safe transport further safety measures need to be taken.

To avoid accidents, ADR provides instructions for how damaged batteries should be carried during transport. LIBs fall under ADR's safety class 9 - Miscellaneous dangerous substances and articles - and the transportation needs to comply with the provisions applicable to UN 3840. The UN number system is used for classification of dangerous goods (Economic Commission for Europe Inland Transport Committee, 2021). Guidelines for how to pack and carry damaged batteries are based on the size and condition of the battery where the packaging instructions P908 (P = Packaging) and LP904 (LP = Large Packaging) apply to damaged batteries. The main difference between the packaging instructions is that LP904 applies to large batteries that are packed individually whereas P908 applies to smaller batteries that can be transported together. However, the following packaging instructions apply in both cases:

1. Each damaged battery must be individually packed in inner packaging and placed inside an outer packaging. If the battery net mass exceeds 30 kilograms, the

battery has to be packed in an individual outer packaging. The inner or outer packaging shall be leak-proof to prevent a potential release of electrolyte.

2. Each inner packaging must be surrounded by sufficient non-combustible and electrically non-conductive thermal insulation material to protect against a dangerous evolution of heat.
3. Sealed packages shall be fitted with a venting device when appropriate.
4. Appropriate measures shall be taken to minimize the effects of vibrations and shocks, prevent movement of the battery within the package that may lead to further damage and a dangerous condition during carriage. Cushioning material that is non-combustible and electrically non-conductive may also be used to meet this requirement.
5. Non combustibility shall be assessed according to a standard recognized in the country where the packaging is designed or manufactured.

Also, both instructions state that for leaking batteries, sufficient inert absorbent material shall be added to the inner or outer packaging to absorb any release of electrolyte and that batteries shall be protected against a short circuit. It is also mentioned that the packaging must be made of either steel, aluminum, rigid plastics, plywood or other metals where further weight restrictions apply depending on the choice of material.

In addition to the instructions above, the package used for transporting damaged batteries must be marked with the text “Damaged/defective lithium-ion” and the transport document must include the statement “Transport in accordance with special provision 376”. The package that carries the battery must also be marked with the sign in *Figure 2.3* which displays the correct UN number.

Lithium battery mark

* Place for UN number(s)

** Place for telephone number for additional information

Figure 2.3: The lithium battery mark that a package carrying damaged lithium-ion batteries must wear (Economic Commission for Europe Inland Transport Committee, 2021).

Finally, the packaging instructions P911 and LP906 are out of scope for this study since they instruct how to package batteries that are severely damaged and liable to cause an accident under normal conditions of carriage. These batteries are equivalent to the classification red batteries which are out of the thesis scope (see *1.4 Focus and delimitation*).

2.2 Supply Chain Theory

This section covers relevant supply chain theory used in this thesis. Generally, the thesis relies on a basic understanding of supply chain mechanisms, however, here some of the more prominently used models and theories are presented and described. The thesis purpose is to explore if and how a unified packaging solution can improve the supply chain performance of an EVB recycler. Addressing this purpose and answering the research question involves some general supply chain concepts. Prominent concepts involved are standardization, differentiation, supply chain strategy, and the importance of having a customer centric approach and identifying customer interaction points. These concepts are described in the section below.

Before addressing these concepts, a general understanding of the term supply chain and supply chain management (SCM) is needed. Typically, the term supply chain is more common and better understood than SCM (Mentzer, 2001). A supply chain exists where there is an operation with connected processes and actors, regardless of if it is managed or not. And Mentzer defines the supply chain as *"a set of three or more entities directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer"*. However, the term supply chain management can have slightly different meanings and definitions. Mentzer proposes three main definitions, where SCM can be defined as either a management philosophy, a set of activities aiming to implement a management philosophy, or as a set of management processes. This ambiguity is later clarified where the first definition, SCM as a philosophy, more accurately is named supply chain orientation (SCO) and the term SCM is defined as *"the sum total of all management actions used to realize the philosophy".* With the definition of a supply chain, and what the concept of SCM implies, four general concepts connected to SCM are now presented.

Standardization

Standardization, or simplification, corresponds to principle five of Persson's nine principles (Persson, G., 1995) for process improvement. The idea behind standardization is to reduce complexity of operations, and thereby achieve an increased efficiency and focus on core activities. Persson highlights this as a strategy for supply chain improvement, and an article by Perona and Miragliotta concludes that there is a relation between low levels of complexity and superior supply chain efficiency and effectiveness (Perona and Miragliotta, 2004). There is also research highlighting the relation between standardizing products and supply chain design, and how the former can improve the supply chain efficiency (Baud-Lavigne, Agard and Penz, 2012).

Connected to standardization, there is a conceptual distinction between efficient and effective supply chain design and performance (Hayes R., Wheelwright, S., 1979). Here, standardization is often related to activities promoting efficient supply chain design. This usually occurs in more mature markets where product designs are less likely to change. Consequently, the standardization level is often related to costs, where a low level of standardization often results in greater logistics costs (Pålsson, 2018). This further relates to the connection between market maturity and the innovation process described by Abernathy and Utterback (Abernathy and Utterback, 1978). Described in the article, process innovation and standardization occur when the dominant design is established on the market and market shares no longer are gained by production performance, but process efficiency and cost cutting.

Differentiation

Another principle for improved supply chain processes proposed by Persson is differentiation (Persson, G., 1995). The idea behind the principle is that a large set of products can be categorized in smaller groups based on attributes. By dividing them into categories, the new groups can be managed relatively autonomously, reducing the need for coordination between them. Often used attributes for categorizations are volumes, sizes, planning horizon or usage frequency.

A frequently used model for supplier differentiation is the Kraljic matrix (van Weele, p. 149-170, 2014). Here, products are categorized based on their supply risk and impact on the financial result. The purpose of this categorization is to apply different purchasing strategies for each group of products, and thereby use the appropriate management strategies for the different groups. This model can be developed further, or adapted to fit other situations, while the differentiating idea stays the same. Another known differentiating method is the pareto method, also known as the 80/20 principle (Ab Talib, Abdul Hamid and Thoo, 2015). It is based on Pareto's finding that 80% of Italy's wealth was distributed on 20% of the people, and in management Svensson and Wood (2006, p. 458) presented in their article that "a small percentage of a total is responsible for a large proportion of total outcome". This has led to a categorization rule applicable to a multitude of situations (Ab Talib, Abdul Hamid and Thoo, 2015). For example, findings that 80% of sales are generated from 20% of the salespeople in a company, or in inventory where 80% of the volumes often are generated from 20% of the SKUs. Due to the method's simplicity and perceived accuracy, it has been widely adopted and deeply rooted in industry (Craft and Leake, 2002). And Ab Talib et. al., further concludes that it is a powerful tool in decision making in supply chain management (Ab Talib, Abdul Hamid and Thoo, 2015).

Supply Chain Strategy

The performance of a supply chain has a significant impact on a company's strategic position and the supply chain should be carefully designed to fit the general strategic direction of the company. One of the most prominent frameworks connecting supply chain strategy with product and process attributes is the product-process matrix by Hayes and Wheelwright (1979). The framework identifies two supply chain attributes, effectiveness, and efficiency, and compares it to the supply chain's product and process qualities. The authors argue that a supply chain strategy should match its product and processes to correspond to an appropriate level of effectiveness and efficiency. For example, a producer of handmade, high performance automotives - a very complex product driven by specific customer requirements and advanced manual processes - should focus their supply chain to be effective rather than efficient to easily respond to customer requests. A large manufacturer of mass produced, less advanced, vehicles should instead focus on an efficient supply chain, valuing low costs and streamlined processes. *Figure 2.4* illustrates the concept of the framework.

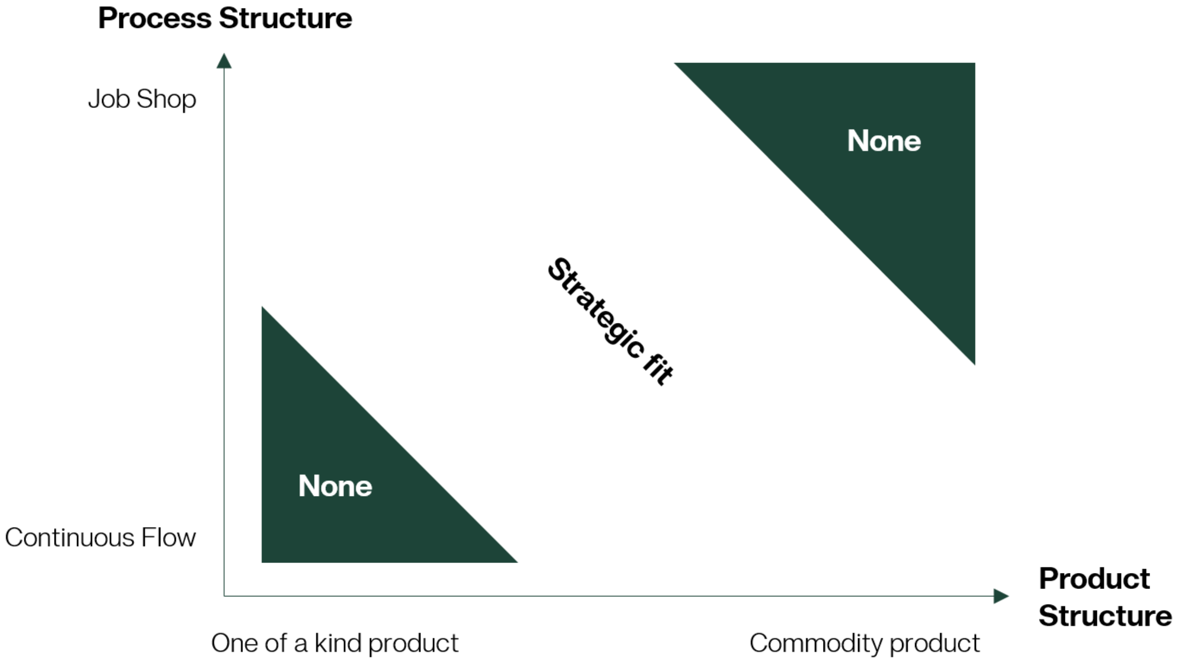


Figure 2.4: The product-process matrix presented by Hayes and Wheelwright (1979) illustrating the strategic fit of a supply chain based on the products and processes involved. (Own illustration)

A Customer Centric Approach

Due to increased competition, shorter product life cycles and less loyal customers, companies are expanding their value propositions to find ways to gain market shares (Madhani, 2019). This has led companies to focus more on the customer, and what drives their buying behavior, their loyalty, and how companies can best serve the customers' needs. Supply chain strategies are not immune to this change, and a so-called customer centric supply chain strategy is becoming more prominent. The customer-centric supply chain strategy is a way of relocating the customer from the end stage of the supply chain, to an ever-present stakeholder affecting the entire supply chain. To achieve this, Madhani suggests four focus areas: responsiveness, resiliency, reliability, and realignment. By pursuing these abilities, companies and supply chains can gain customer and market insights and a competitive advantage compared to others.

As a part of the customer centric approach, focusing on the customer journey has become increasingly important (McKinsey, 2016). Companies often see their interaction points with customers as separate interactions, missing the connection between them. The authors instead suggest companies take a broader perspective and view it from the point of the customer journey, connecting the different touchpoints. By focusing on the customer journey, rather than touchpoints, the company and its supply chain have a better understanding of the customers' needs, and how to best serve them. This approach will lead to higher customer satisfaction, a higher retention rate, and ultimately a competitive advantage. The authors suggest six critical actions to manage the customer journey:

1. Step back and identify the nature of the journeys customers take — from the customer's point of view.
2. Understand how customers navigate across touchpoints as they move through the journey.
3. Anticipate the customer's needs, expectations, and desires during each part of the journey.
4. Build an understanding of what is working and what is not.
5. Set priorities for the most important gaps and opportunities to improve the journey.
6. Come to grips with fixing root-cause issues and redesigning the journeys for a better end-to-end experience.

2.3 Packaging Theory

As a general theme, this section describes the development of a packaging solution and how its design is intertwined with the supply chain performance. The section starts with generally discussing packaging design and how its performance can be evaluated and continues with exploring how the packaging design influences the supply chain, logistical processes and the environment.

2.3.1 Design and Development

Today, packaging is not seen only as a simple box or carton, but as a coordinated system to ensure safe, secure and efficient handling, transport, distribution and storage of goods along a supply chain (Saghir, 2004; Pålsson, pp. 1-16, 2018; Lavanya, 2019). The packaging system can be divided into several levels where the total performance of the system is affected by the performance of each level as well as the interactions between these levels (Saghir, 2004). The first level, called the primary packaging, is the packaging in direct contact with the product itself and it fulfills the purpose to protect the content (Pålsson, pp. 1-16, 2018). The secondary packaging is used outside primary packaging to group a certain number of products whilst the tertiary packaging, also known as the bulk or transit packaging, is used to group a number of secondary packages to facilitate handling during transportation (Pålsson, pp.1-16, 2018). Lastly, a common name for packaging types used in industrial context is transport or industrial packaging which is used to facilitate handling, transport and storage of several primary packages in order to provide efficient distribution as well as prevent physical handling and transport damage. *Figure 2.5* illustrates the general idea for packaging systems.

Product Primary Secondary Tertiary

Figure 2.5: Illustration of a generic packaging system (source: own illustration)

Bowersox (pp. 408-436, 2001) mentions that two of the primary functions of a packaging are protection and communication. The protection needed from packaging can be derived from the environment where it is anticipated to be used. Though important to remember is that the degree of protection should optimally not exceed the maximal required level in order to avoid expenses from overprotection and transportation of extra weight. Further, the communication aspect can serve several purposes. First, labels communicating the content can provide handling and safety instructions for channel members in contact with the package along the supply chain. In the case of transporting EVBs, the packages must display that it contains a battery in order to meet hazard communication requirements (Stallery, 2021). Packaging can also be used as an information source by using communication technology (e.g., RFID). By integrating information from a labeled packaging with the logistics management, a track and trace system can be used to the product and packaging location providing control to the stakeholder in responsibility (Pålsson, pp. 73-86, 2018).

Lastly, Bramklev (2007) concludes that the development processes of the product and the packaging solution need to be integrated and considered when deciding on design parameters. By integrating the two processes product developers and suppliers must collaborate in order to develop an efficient product/packaging system. In an efficient system, the product developers for example need to design a product that fills the packaging while the supplier should design the packaging to fit the product. By integrating the product and packaging development, an increased supply chain efficiency can be achieved, for example in the processes of transportation, logistics, manufacturing and waste management (Pålsson, pp. 128-137, 2018). Yet in many cases this describes an utopian situation that is not feasible in reality. For example, in situations when there is a large product variation, it is not viable to design packages to perfectly fit every unique product design until product standards are established and the design variation is reduced. Therefore, ISO highlights the importance of collaboration between the packaging and product to establish industry standards (ISO, 2023).

2.3.2 Packaging Logistics

Industrial packaging is typically focused on logistics where the primary concern is to achieve the best possible logistical efficiency (Bowersox, pp. 408-436, 2001; Pålson, pp. 99-111, 2018). The field that combines packaging and logistics is often referred to as packaging logistics and has the potential to reduce supply chain costs and its environmental impact (Pålsson, pp. 1-16, 2018). Research on the topic emphasizes that it is crucial to apply a holistic system approach to develop cost-efficient packaging systems with minimal environmental impact across the supply chain. While a well-designed system may help in pinpointing trade-offs and interactions between its parts, a poorly designed packaging system may make the entire logistics system performance suffer.

Packaging affects every logistics activity (Bowersox, pp. 408-436, 2001) and from an environmental perspective, the influence of packaging on logistical efficiency is mainly related to the energy use of logistical processes (Molina-Besch, K., Pålsson, H., 2016). For instance the packaging design affects the transport utilization while the material choice affects waste management and recycling (Pålsson, pp. 1-16, 2018). Hence to reduce the environmental impact and to improve the logistics efficiency, packaging designers should keep the two approaches in mind; maximize the fill rate during transport and storage and unitization in the packaging system (Molina-Besch, K., Pålsson, H., 2016).

Maximize the fill rate

Factors influencing the transport utilization and fill rate are for example the product volume and weight, packaging system volume and weight, dimensions of the transport vehicles, and transport planning (e.g. frequency and shipment sizes) (Molina-Besch, K., Pålsson, H., 2016). While it may seem obvious that a well-designed packaging system can better utilize a transport, Wever (2011) concludes that a higher fill rate could also reduce energy consumption from stationary logistic facilities (such as warehouses, distribution centers, ports) because of the decreased need for storage space and handling. In a literature study, (Molina-Besch, K., Pålsson, H., 2016), summarizes a handful of packaging approaches that can potentially contribute to a higher fill rate along the supply chain:

1. Maximizing the fill rate in all levels of the packaging system (Nilsson et al, 2011; Pålsson et al, 2013): This means that the packaging levels should be designed with each other in mind, where for example a secondary packaging should be designed fit a certain number of primary packages

2. Adapting the packaging system to the transport vehicle dimensions (Hellström, 2011): Packaging developers need to identify what load-carriers that will be used along the value chain and find a design that fit their dimensions
3. Developing modularized a packaging design to fit a variety of different products on one load carrier (Santén, 2012): A modularized design gives a possibility to pack a variety of products while still benefiting from a standardized packaging design
4. Developing stackable packaging (Santén, 2012): The design has to be robust enough to enable stacking of packages in transport vehicles and stationary storage
5. Minimizing volume of empty packaging (Pålsson et al, 2013; Jahre, 2004): Having foldable packages saves space when transporting empty packages in the reversed flow or when in the warehouse
6. Minimizing packaging material weight (Blinge, 2005): By reducing the material weight of the packaging, less unnecessary weight is transported which for example decreases the emissions

In the same literature study, (Molina-Besch, K., Pålsson, H., 2016) also mentions a few barriers when designing for a maximized fill rate. First, it may not be technically possible to construct products in dimensions that fit well with load carriers or transport vehicles. This problem may be especially prominent for new products where a design standard is yet to be developed. Another potential barrier is the variety of transport modes and the different standards being used around the world. It may be difficult to design a packaging solution that fully utilizes all types of transport modes. Lastly, problems may also arise from customers ordering small quantities or a wide variety of products with varying dimensions which might cause unutilized transportation.

Optimize design for unitization

Another way a well-designed packaging system may improve the efficiency of the logistics and material handling is through unitization (Pålsson, pp. 1-16, 2018). Unitization means that smaller units are gathered into larger ones to decrease the number of units handled along a supply chain (Nilsson, F., et al, 2011; Pålsson, pp. 1-16, 2018). Unitization is often achieved through modularization of the packaging system, where the packaging levels are designed to fit each other well (e.g. fit a certain number of primary packages into a secondary package) (Pålsson, pp. 1-16, 2018). There are several benefits with unitization, where increased logistics efficiency is a prominent one. Since it is easier to handle larger units than individual ones, a unitized package often results in more efficient material handling which saves unloading time, reduces costs and increases productivity (Bowersox, pp. 408-436, 2001; Moon, 2011). Another benefit with unitization is reduced shipping costs which could be achieved by consolidating packages into larger transport units and thus sending fewer shipments (Bowersox, pp. 408-436, 2001).

However, to enable unitization there might be a need for consolidating products. Consolidation means that products are gathered at collection points before further shipment to ensure that the amount of products is enough to fill a unit (Moon, 2011). This could be done by postponing the flow of products in interim storage until the levels are high enough to fill a load carrier.

2.3.3 Standardization and Modularity

In situations when a packaging is developed towards an undeveloped market with a high product variability, it is beneficial if it can be flexible. In such a context, flexibility can help the packaging design sustain longer if it is able to handle the variability of known and still undeveloped products. One way to achieve a flexible packaging system while still not designing specific solutions for each product is using a modular design (Karlsson, 2013). Modularity in packaging design refers to the use of interchangeable, standardized components that can be assembled in different ways to create a variety of packaging solutions.

There are several ways in which a packaging design could benefit from modularity. First of all, modular packages provide flexibility by adjusting the design using standard components such as incerts (de Blok et. al., 2010). This gives the possibility to customize the design, without the need for extensive work to design individual solutions (Muffato, 1999). Flexibility is especially beneficial when the product dimensions vary and enables efficiently packing of more products than if the design was fixed. A modular design can also save costs by focusing the production on manufacturing standardized components leading to economies of scale (Karlsson, 2013). With a modular design, it could also be easier to collapse the package to save space making the reverse transportation more efficient. Finally, modularity can also be sustainably beneficial since the package can be repaired or individual parts can be changed instead of disposing of the entire package (Pekkarinen & Ulkuniemi, 2008).

On the weaker side, a modular design could be less robust than a fixed design. That is a reason why extensive product tests need to be carried out in an environment similar to the one where the package is anticipated to be used to see whether it meets the requirements. Also, while a modularized or standardized packaging solution may be efficient for handling today’s products, it may cause negative lock-in effects if not fitting future flows of products (Pålsson, pp. 18-25, 2018). For example, by changes in the product assortment or in the supply chain.

2.3.4 Environmental Impact

A well-designed packaging solution can provide both logistics efficiency and a positive sustainability impact since they often come hand in hand. The environmental impact from a packaging design can be seen both as direct and indirect (Molina-Besch, K., Pålsson, H., 2016). The direct impact can be derived from the packaging material, in terms of the environmental impact during its production and the packaging waste (Pålsson, 2018). One way to reduce it is by optimizing the material used in the package as well as avoiding the inclusion of hazardous substances. Direct impact may also be reduced from developing a package that is efficient for reuse, recycling and recovery.

Returnable packages is a way to make packages reusable, which is appropriate in integrated environments where there is a controlled closed loop between shipper and customer (Bowersox, pp. 408-436, 2001). Returnable packages are designed for reuse without losing their protective function. When investing in a returnable packaging solution, the total costs must be compared with the number of shipment cycles, including costs such as return transportation and storage costs. This investment is then compared to the purchase and disposal cost of one-time containers (Bowersox, pp. 408-436, 2001; Pålsson, pp. 87-98, 2018). Using a returnable packaging system can also help with recycling the packages when reaching their end-of-life since it is easier to collect them from a closed loop (Kuczenski, 2010).

On the other hand, a package's indirect environmental impact is connected to its impact on logistics efficiency and its capability to prevent product waste (Pålsson, 2018). An example of an indirect impact is the packaging's contribution to logistical efficiency and the degree to which it utilizes transport and storage space which has been discussed previously in this chapter.

2.3.5 Evaluating Design Performance

The purpose of the study was to evaluate packaging design and its logistics performance. A framework that has been used as guidance to the thesis problem-solving approach is one designed by Pålsson (pp. 27-42, 2018). The framework considers both qualitative and quantitative aspects when evaluating the performance and consists of four main steps, which have been adapted to fit the purpose of the study. The steps are illustrated by *Figure 2.6*.

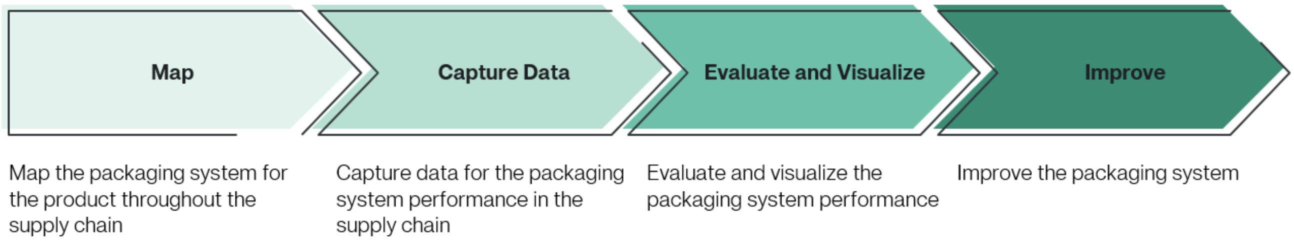


Figure 2.6: Illustration of Pålsson's four steps in evaluating a packaging design. (Source: own illustration)

The first step aims to understand the context and its stakeholders - the packaging system, the supply chain and the product. The basis is to understand the characteristics of the product that the package is aimed for and how they impact the packaging system. For example, the price of the product can affect what costs are feasible for the packaging. If the product is expensive, it might be able to bear higher packaging costs without impacting the margins, while if it is a cheap product, it has a larger impact. Next, the actors and activities involved in the supply chain need to be mapped. It is also relevant to map the interaction points between these actors and the packaging system. As a final activity for the mapping step, it is important to make a list of the product-specific challenges which for example could include high variation in product dimensions or weather sensitivity.

The next step of the framework is capturing data for how the packaging system performs in the supply chain. According to Pålsson, the performance is evaluated based on three areas: obtaining logistics efficiency, being value-adding and minimizing packaging material. Packaging and its relation to logistics efficiency has been discussed previously, however examples of value-adding aspects could be that the package provides information about the product or promotes itself and the content with branding. Actions to minimize the packaging material could for example be reducing the cost or waste but also the ease of opening the package.

The third phase of the framework is evaluating the packaging performance. The evaluation must be adapted to the situation by choosing evaluation parameters that provide useful insights for the case. For example, packaging designs can be evaluated based on their environmental impact or how it contributes to logistical efficiency.

Lastly, following the evaluation phase is a concluding phase which benchmarks the design against other packaging systems in order to find improvement areas. Besides comparing the design performance to other solutions, it is also suitable to analyze different scenarios where design parameters, such as volume or weight, are tuned to find the best possible design for the packaging solution (Maack pp. 62-63, 2001).

2.4 Literature Framework

Summarizing the literature review, relevant theory to this study comes from three separate areas, where the interception of them provides valuable insights for a battery recycler. By combining the findings from each area, they serve as an investigation framework to be used when further exploring whether a battery recycler would benefit from offering a unified packaging and logistics solution. The three areas and relevant topics within them are summarized in the theoretical framework seen in *Figure 2.7*.

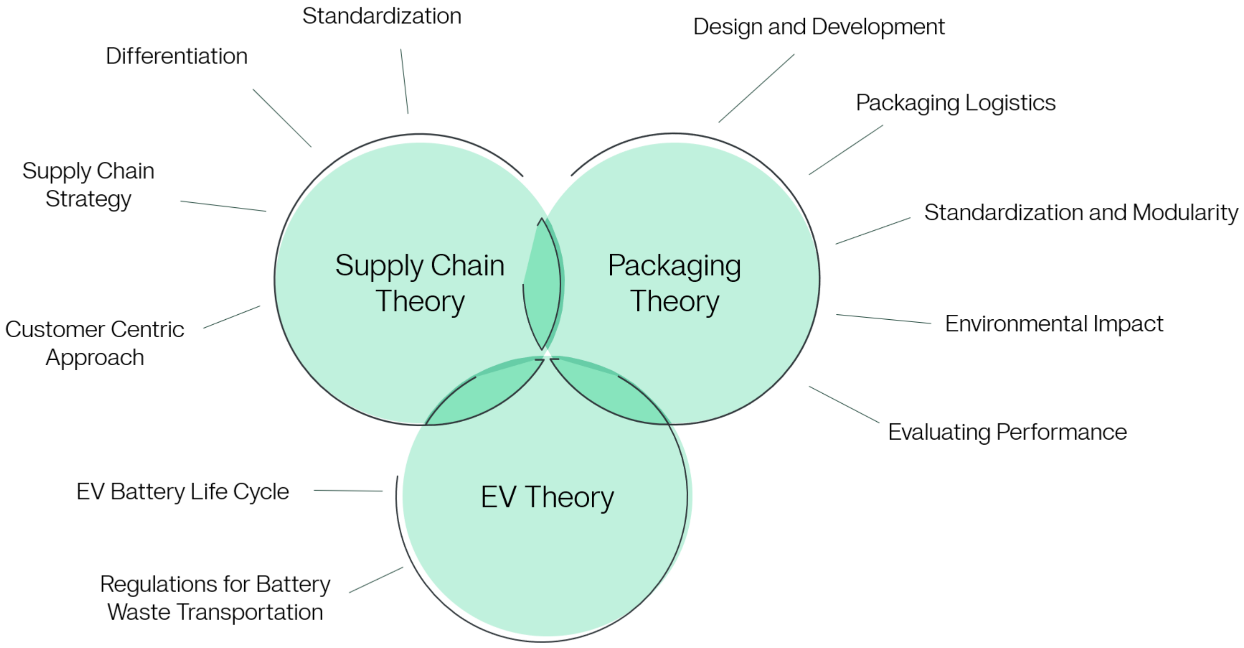


Figure 2.7. Illustration of the theoretical framework supporting the thesis (Source: own illustration)

First, what frames the thesis is the theory about EVBs, their lifecycle and how the transportation of them is regulated. To be able to design a suitable packaging solution for recycling batteries it is necessary to understand their nature. The theory highlights the complexity of batteries and that the flows to recycling occur during multiple steps in their life. Additionally, from a theoretical point of view there is a clear case for recycling of batteries where both economic, environmental, and geopolitical arguments are presented. However, what complicates the collection of batteries is the ADR regulated transport which has to be considered when designing the packaging and logistics setup.

Next, the section regarding supply chain theory provides a handful of useful ideas and concepts to be used when setting up a supply chain for collecting EVBs from OEMs to recycling. Differentiation will be relevant when studying the batteries for which the packaging is aimed towards. It helps with identifying patterns and subgroups within the large sample of batteries on the market which gives a better understanding for the requirements on the package coming from the products. The concept of a customer centric supply chain also highlights the significance of having the customer interaction points in mind when establishing the supply chain to keep customers satisfied. However, ultimately this customer centric perspective must be aligned with the overarching business- and supply chain strategy for it to be viable to the recycler as well. Lastly, the strategic connection between supply chain operations and general business strategy is an important aspect to ensure long-lasting and sustainable results from a new packaging solution.

Moving on to the packaging theory, it highlights that new products under development and design changes require more from the packaging. This is important to consider when designing packaging for EVBs since they are still in an early development phase and have varying dimensions. Since it is not feasible to design unique packaging for every battery dimension, one promising path to explore is the usage of a flexible or modular design.

The literature review chapter is rounded off by presenting Pålsson’s framework for evaluating the performance of a packaging system design. With the previous theoretical findings in mind, this framework provides guidance in having a systematic approach to investigating the thesis purpose. The first and second framework step provided structure for the mapping of the packaging system and its context where it will be used, as well as the collection performance data. Whereas the third and fourth steps are later found in the analysis part where the packaging system performance is evaluated. These framework steps have been adapted to fit the purpose of this study by choosing evaluation parameters that provide useful insights. For example, packaging designs will be evaluated based on transport and storage efficiency as well as a comparison between the share of the battery recycling market that the design captures (which will generate revenues) and its costs.

3. Methodology

The methodology chapter presents how the thesis is designed and conducted. To provide transparency and a connection between the study's purpose and its conclusions, the content of this chapter aims to describe how and why the study was performed in its particular way. The chapter starts by presenting the research strategy, moving on to the research design including methods for data collection and analysis and is finally concluded with a brief discussion of the thesis' research quality.

3.1 Research Strategy

This section introduces different research methodologies to present the thesis' research strategy and in particular motivating why a certain method and methodology has been selected.

3.1.1 Research Methodology

To fulfill the research purpose, the overall strategy must be decided as a first step. As previously stated, the purpose of the study is exploring whether a battery recycler could benefit from offering a packaging and logistics solution for recycling batteries. Due to the characteristics of the research question and the purpose of the thesis, an exploratory approach is the most fitting. This is supported mainly by two arguments, both originating from Yin (2003). Firstly, an exploratory approach is useful when researching a subject where established knowledge is scarce. This is the case for the European EVB market which is still in its early stages and lacks a unified solution for recycling batteries, and the logistics surrounding it. The second argument is that an exploratory approach stimulates further studies or projects to be conducted within the same field which would be beneficial when developing a standard for logistics connected to battery recycling in Europe.

3.1.2 Research Method

This thesis will rely on a case study, where a phenomenon will be analyzed in its real-world context, as a research method (Robson and McCartan, pp. 145-173, 2016). The decision is based on Yin's (2003) three main components when deciding on which research method to use in a study. First, the type of research question posed is categorized as a "how" question. These questions usually benefit from case studies, histories, or experiments. Second, reviewing the need for control of events, the posed question does not need a controlled environment to be answered. Hence, the experimental approach can be disregarded as a research method. Lastly, the studied events are contemporary due to their connection to today's immature and fast-moving market for battery recycling packaging - and its lack of conventional solutions. The study will include direct observations of the events included, and interviews with key stakeholders directly involved with the studied events. These are two aspects only applied to case studies, thus motivating the thesis' research method of choice.

Case studies are built up by four main phases: planning and design; preparation; gathering and analysis of data; and sharing the result (Yin, 2003). The initial planning and design phase was iterative and conducted together with supervisors both from LTH and the case company, resulting in the thesis' purpose, scope, research question and objectives, and a project plan. The following preparation phase was mainly conducted by the thesis authors. Here, the focus lies on creating a literature framework outlining a theoretical base, as well as understanding the components affecting the result of the thesis. The phase for gathering and analysis of data consists of four main parts: a literature study; expert interviews; qualitative data analysis at the case company; and quantitative data analysis at the case company. The objective of this phase is to build arguments addressing the research objective, and further answer the posed research question. Lastly, the fourth phase concerns the sharing of results. This was continuously done during the thesis work, however, there was an amplification of information sharing during the end of the project. This is due to the thesis' iterative nature, and the validation work conducted together with LTH and the case company to ensure the relevance and validity of the analysis and conclusions.

Continuing, Yin (2003) identifies four types of cases, separated on whether they follow a single-case or multiple-case design, and if they have a holistic (single unit of analysis) or embedded (multiple units of analysis) approach. This is illustrated by *Figure 3.1.* Deducted from the purpose and research question, and described in section *3.1.3 Unit of analysis*, this thesis will study a single case company, investigating a single unit of analysis. Therefore, the thesis will follow the design of a holistic single-case study. Lastly, while a single-case study provides great depth, it must also be remembered that it might provide limited possibilities to generalize the conclusions.

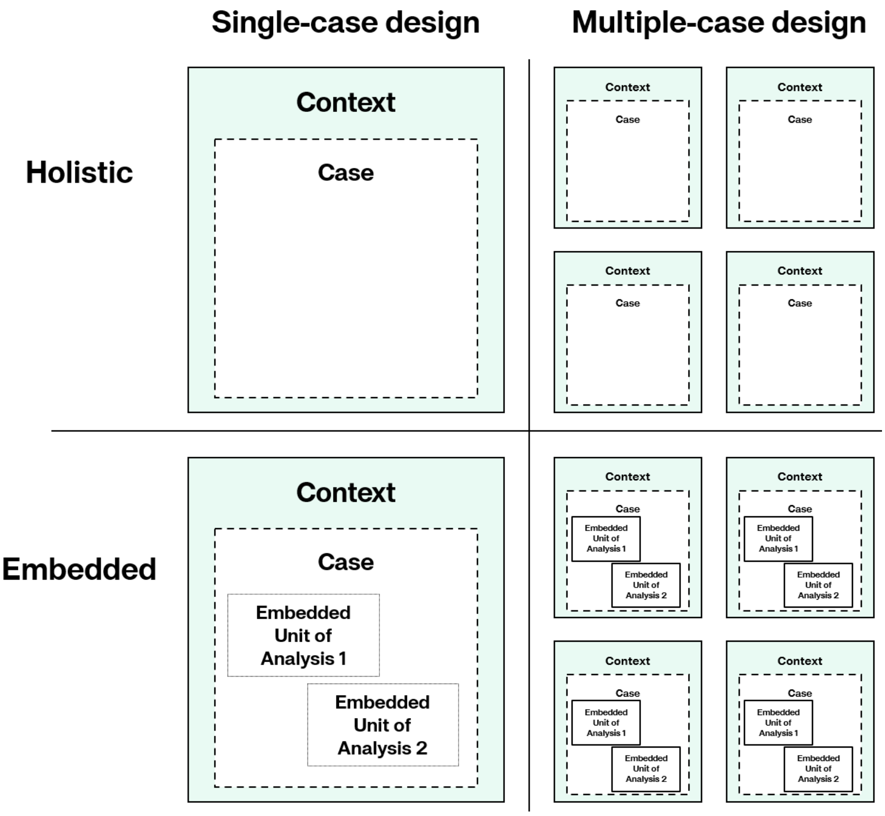


Figure 3.1: The four different case types presented by Yin (2003) (Source: own illustration adopted from Yin (2003))

3.2 Research Design

Once the overall research strategy was decided, a research design was developed which originated from the purpose of the study. The design provided guidance while conducting the study and support for data collection and analysis. This chapter aims to describe the research design in detail together with the different steps included.

As previously stated, the purpose of this master thesis is to explore whether a recycler would benefit from offering a packaging and logistics solution for battery recycling to OEMs. Therefore, instead of limiting this analysis to solely a general discussion, the study was designed to evaluate a case company active within the recycling industry. The research design allowed data collection from a real-world setting, as well as conclusions based on realistic scenarios, applicable also for other battery recycling actors.

Further, an overview of the research design is seen in *Figure 3.2*, illustrating the steps and activities included in the study. As seen in *Figure 3.2,* the research design consists of four main elements, further divided into activities. The elements are the define and design phase, collection of empirical data, the analysis, and finally the evaluation and conclusion phase. The feedback loop from the case company and university is also mapped in the figure. In practice, the feedback mainly comes from meetings and workshops. This chapter describes each of the four elements in detail and elaborates on each activity.

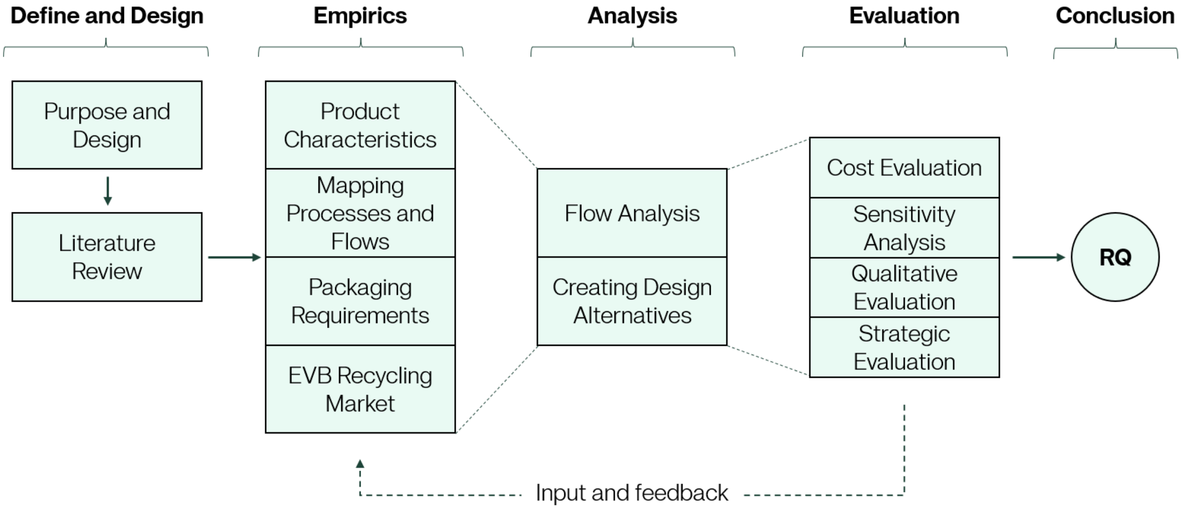


Figure 3.2: Overview of the research design consisting of the four elements; define and design, data collection, data analysis and conclusion. (Source: own illustration)

3.2.1 The Case Company

The case company chosen for this thesis is an EVB recycler operating in Europe. They run a small-scale recycling operation today, planning to expand during the coming years. The reason this company was selected is that they have extensive knowledge within the battery field, as well as experienced logisticians and packaging engineers willing to support the thesis. The company is also currently lacking a unified packaging solution, making the thesis highly relevant for their future operations. By choosing a company with large interest in the research question, they have a good incentive in supporting the authors in the thesis process.

3.2.2 Unit of Analysis

A Unit of Analysis (UoA) refers to the phenomenon or entity being studied (Yin, 2003). A well-defined UoA allows researchers to address the correct purpose and provides guidance in exploring the research questions. In this single case study, the UoA is the circular supply chain for a packaging solution for EVB recycling, applied in the setting of a case company. It is illustrated in *Figure 3.3* and by evaluating the problem from the case company's point of view, more realistic conclusions and recommendations can be drawn than if the same analysis would have been general. The supply chain takes place in different geographical locations and involves activities associated with the handling at the OEM site, during the transportation, and at the internal site of a battery recycler. Further, the study expands the perspective to also include the design, sourcing, and recycling phase of the packaging's life cycle in addition to its use phase. The decision of a UoA later guided the thesis in the method selection for data collection and analysis which are presented in the following chapters.

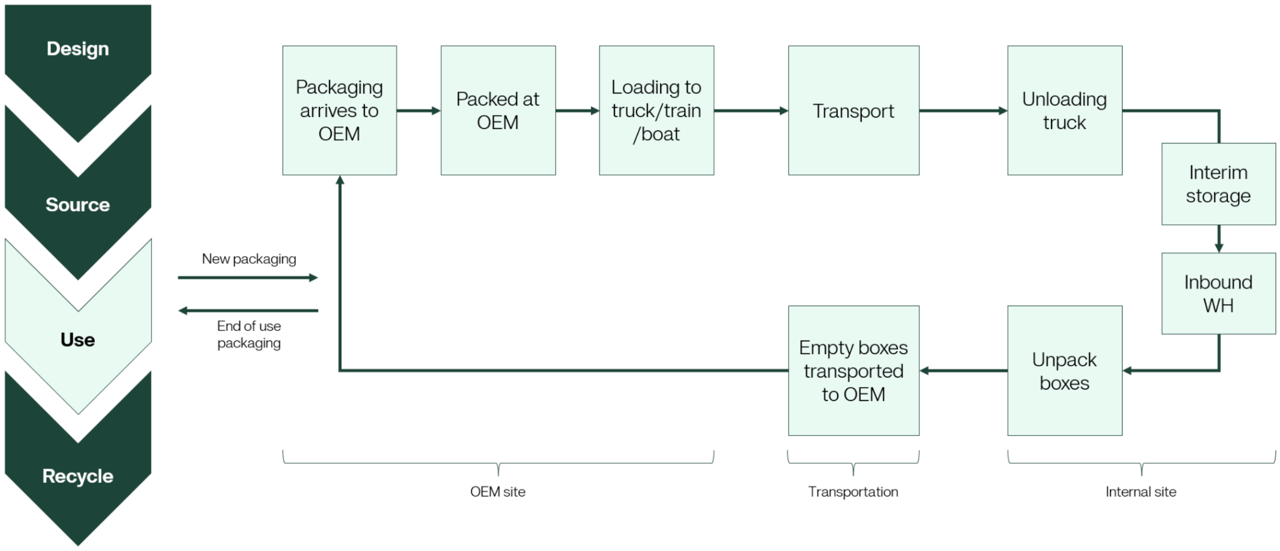


Figure 3.3: Unit of analysis, illustrating the steps that a packaging for battery recycling goes through. (Source: own illustration)

3.3 Data Collection

After determining the overall research design, a collection protocol is designed (Yin, 2014 p. 60). The data collection is divided into four subparts: the product characteristics, the process- and product flow, the packaging requirements, and lastly the market for battery recycling. Data presented in this part of the thesis is collected from both reviewing literature and interviews, and the respective strategy is described below.

The first part of the empirics chapter presents different product-related data (e.g. dimensions and weight) from packs and modules. Next, the process map zooms out to illustrate the flow for how an EOL EVB moves from its source (e.g., OEMs, scrapyard etc.) to the recycling plant. This map illustrates what interaction points the battery and its packaging solution will meet along the process. The product map, on the other hand, presents data on the EVBs with the largest presence on the market. Thirdly, a stakeholder mapping is made where their requirements on the packaging solution are compiled. The fourth empirics part evaluates the battery recycling market. In short it presents estimates for future growth of the EV market and the EVB recycling market, as well as trends within the EV industry.

The data collection was conducted between January and April 2023, and the interviews held included people both within and outside of the case company. The qualitative and quantitative methods are further described in their subsections below and were initially performed iteratively to help build a fundamental understanding of the subject, and to be more flexible. The theoretical framework was developed in the form of a conceptual map where key theoretical areas or pools for the thesis were identified, see *Figure 3.4* in section *3.3.2 Literature Review* (Rowley J., Slack F., 2004). The map supports the thesis by mapping the theories and concepts on the research topic, clarifying the structure of the literature review and report as well as identifying additional search terms for the literature search. After the initial knowledge-building phase, the data gathering was complemented with in-depth interviews and more niche literature search.

3.3.1 Interviews

The interviews performed for this thesis collected both qualitative and quantitative data and can be divided into two phases. The initial phase focused on gaining a basic understanding for the thesis subject as well as limiting the scope. The initial interviews were solely performed internally at the case company with different key stakeholders. In general, these interviews addressed questions based on the theoretical framework. This for example concerned the current EV battery recycling market, regulations for transporting battery waste, and conceptual discussions on process steps. Another result from the interviews was access to various datasets (e.g., battery dimensions, market trends etc.) that laid the foundation for the thesis' analysis part. Whereas the later interview phase complemented the primary phase with in-depth interviews asking more specific questions. *Figure 3.4* illustrates the different interviews and their respective focus areas.

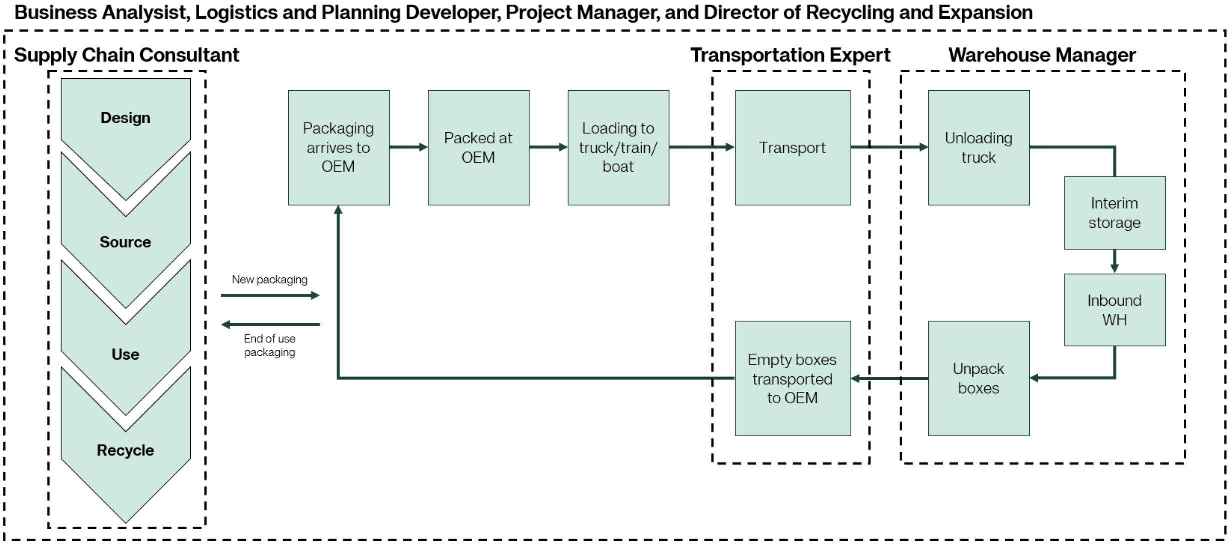


Figure 3.4: Illustration of the focus area from each interview.

To cover these aspects people from the case company working as business analyst, logistics and planning developer, project manager, amongst others were interviewed. They were asked the questions compiled in *Appendix A: Interview Guide* which were centered around the thesis' theoretical framework as well as interviewee's specific knowledge.

3.3.2 Literature Review

The data from the interviews has been compared to and supplemented by a literature review. As a basis for the literature review, the theoretical framework seen in *Figure 2.7* was developed, providing guidance on the three main academic subjects to be investigated. The approach to reviewing literature evolved gradually during the thesis as the understanding of the field grew. In the initial phase an approach called “citation pearl growing” was used, which identifies keywords to get an overview of the areas being explored (Rowley J., Slack F., 2004). These keywords are used to find relevant articles and references which in turn are used to further deepen the knowledge. Finally, as a general approach, triangulation between academic papers has been used as a strategy to increase the credibility of separate arguments as well as the whole study (Robson and McCartan, pp. 145-173, 2016).

Going through the theoretical framework, seen in *Figure 2.7*, the first part aims to understand the product being packed - EV batteries. Articles included in this part describe qualities of the battery, steps of the battery life cycle and regulatory requirements applicable to the product. The second part addresses supply chain theory, outlining supply chain assessments, analysis methods and supply chain principles. These areas are addressed mainly to support the empirics and analysis part of this thesis, guiding the solution approach. Lastly, the third part of the theoretical framework focuses on packaging theory and its relation to the supply chain. This subject technically touches the sub-area of supply chain theory, however, since the thesis centers around packaging it is here seen as a free-standing area for the literature review. As a rule of thumb, the section on supply chain theory will cover areas addressing the larger flows, whereas packaging logistics will focus on the packaging and the effect it has on logistics.

Conducting the literature review, search engines such as *Google Scholar* and *LubSearch* assisted in finding peer-reviewed articles. In total 80 articles were read, and to help narrow the search, key words, and phrases such as “packaging logistics”, “EV batteries”, “recycling EVB”, “EV Life Cycle”, “EVB recycling supply chain”, “supply chain performance improvement”, and “EV market growth estimates” were used. To find journals, sites such as *Emerald* and *ScienceDirect* were used. From them examples of journals used are *Journal of Cleaner Production, International Journal of Physical Distribution & Logistics Management,* and *Technological Forecasting and Social Change*. To ensure the quality of the information, one criterion for articles included in this thesis was that they had to be peer-reviewed. This has however been overruled on some occasions where data has been collected from other sources, situations handled with extra caution by the authors.

3.4 Data Analysis and Evaluation

After setting up a data collection protocol, the next step in deciding on the research design was establishing a strategy for analyzing and evaluating the collected data (Yin, 2014 p. 60). The data analysis of the study focuses on the operational setup resulting from choosing different packaging solutions. The evaluation then aims to compare these setups and their performance to support an EVB recycler in making an informed and strategically aligned decision for their packaging solution. The structure of the analysis and evaluation is explained in further detail below, while a visual overview can be seen in earlier presented *Figure 3.2*.

Data Analysis

To appropriately design a packaging and logistics solution, the first analysis aims to understand the flow of EVBs. The flow analysis is divided into three subparts where it starts off by categorizing the battery data into four archetypes which form a foundation for the packaging design. The archetypes illustrate four different dimension setups which in the next step are used to investigate the market to see the distribution between them. This analysis gives an understanding of EVB shapes on the market, and if a dominant design is emerging which would indicate that the market is ready for process innovation. Included in the flow analysis is also the estimated future flow of EVBs. The flow analysis is based on both expert interviews and forecasts. It therefore provides information to design a packaging solution that is viable in the long term, not only capturing EVBs on the market as of today.

The data analysis then presents an operational model created to test different design alternatives and their operational qualities. This model is further accompanied by five design alternatives representing different market strategies with varying market shares. Combining the operational model with these design alternatives, the data analysis is concluded by the operational performance of each alternative.

Evaluating Design Alternatives

The second step of the analysis is to evaluate the performance of the packaging designs presented in the analysis. The evaluation considers the packaging's captured market share, its direct and indirect costs, handling and transportation efficiency, and other parameters highlighted as important by the case company and literature. The design alternatives are evaluated from a commercial point of view where both quantitative and qualitative measures are considered. The evaluation investigates whether a battery recycler can benefit, financially or strategically, from offering a packaging and logistics solution for battery recycling. This type of evaluation corresponds to the third and fourth step in Pålsson's framework described in *2.3.5 Framework for Evaluating Packaging Design Performance*.

Going through the four evaluation steps, the design alternatives are first evaluated on their financial performance. In this step, costs are added to the operational model presented in the data analysis and each design alternative is compared to a baseline case. This model is referred to as the cost comparison model and a snapshot of it can be seen in Appendix D: Financial Model in Excel. By doing this, the potential cost savings can be highlighted for each design alternative.

Secondly, a sensitivity analysis of the cost comparison model and the design alternatives' performance is presented. This part aims to evaluate the robustness of the model and the alternatives' performance to ensure a reliable result.

Thirdly, the qualitative aspects of the case evaluation are presented. They are seen as complementary decisions necessary to achieve a strategic fit between the packaging solution and the recycler's overall business strategy. A qualitative aspect can for example be the material choice, where a more expensive and complex material can be better in some strategic settings and seen as excessive in others.

Lastly, the design alternatives are evaluated from a strategic point of view and connected to different supply chain strategies. This is the final step of the evaluation process and by following this process an EVB recycler will be able to successfully find a packaging solution fitting their needs and strategic direction.

3.5 Research Quality

An important part when publishing a study's trustworthiness and credibility is research quality. When evaluating a study's research quality it is often examined by its reliability and its validity, discussed in the following respective subsections (Yin, 2003).

3.5.1 Reliability

Reliability measures a method's consistency over time and with different observers (Robson and McCartan, pp. 145-173, 2016). Essentially what this means is that if another researcher would repeat the same research design as the original, they would arrive at the same findings and conclusions (Yin, 2003) (Robson and McCartan, pp. 145-173,, 2016). The aim is then to minimize any biases in a study which is why the research design has to be thoroughly explained. Therefore, if a result is consistently achieved using the same methods and circumstances, the measurement is considered reliable.

Triangulation is used as a common strategy in academia to increase the rigor of a study (Robson & McCartan, pp. 145-173, 2016). Theory triangulation means that a researcher uses multiple theories or perspectives to corroborate a statement which reduces the risk of including any biases from using a single method or observation (Noble & Heale, 2019). Triangulation between sources was therefore used to make sure that the literature review had high reliability (Rowley J., Slack F., 2004). Another strategy to establish trustworthiness and provide reliable results was to collect all data in a structured database that is presented in *Appendix B: Most Sold EVs* (Yin, 2003).

3.5.2 Validity

The term validity regards the accuracy of a study, meaning that it should be accurate and measure what it is intended to (Robson and McCartan, pp. 145-173, 2016). Often, it is divided into three subcategories: (1) construct validity, (2) external validity and (3) internal validity (Yin, 2003).

Construct validity is defined as “establishing correct operational measures for the concept being studied” which means how well a method explains a phenomenon studied (Yin, 2003). An approach used to establish construct validity was dividing the data analysis into clear and multiple steps which provides a chain of evidence (Yin, 2003). According to the same theory, another approach is to use multiple sources of evidence. In addition, during the thesis the result and analysis have been presented to the case company in workshops aiming to validate the conclusions. This iterative process has enabled a higher level of construct validity and a more trustworthy conclusion.

External validity is often referred to as generalizability and means whether the findings in a study hold when the context changes (Yin, 2003). In accordance with Yin’s theory (2003), a tactic used to ensure external validity was to compare the results gained from the case company to the results from the literature review. This comparison was necessary since the study was designed as a single-case study so there were no other case companies to compare with.

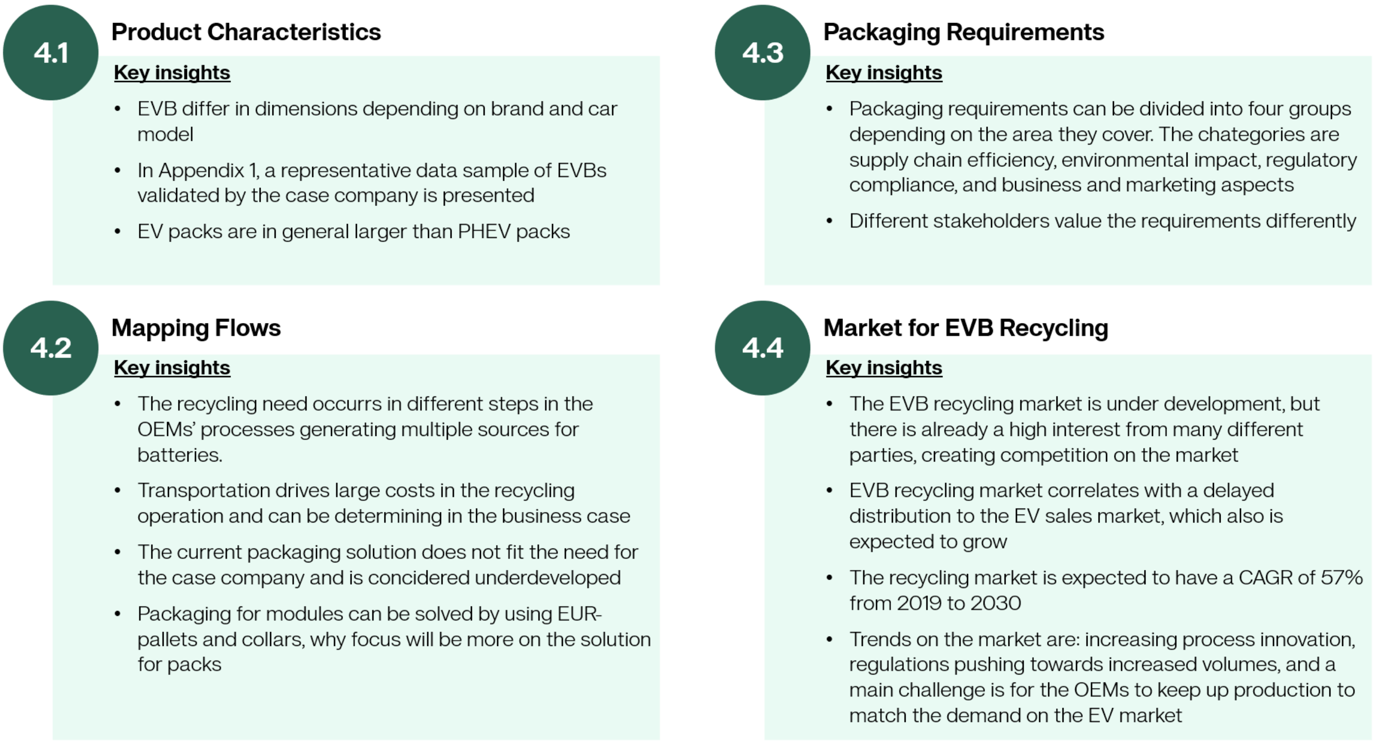
Lastly, the key question in internal validity concerns whether there is a causal relationship between two variables or if the relationship is influenced by a confounding variable, meaning that there is a bias (Sargeant, 2022). However, internal validity is not relevant in this case study since it does not try to explain a causal relation where one event causes another. It is more frequently seen in explanatory or causal studies (Yin, 2003).

3.5.3 Ethics and Social Aspects

Before diving into the empirics, a discussion about this study’s ethical and social impact is presented. Since the study has not included any tests or experiments, it has not had any external effects during the writing process. However, if a unified packaging and logistics solution will be implemented by a battery recycler, it will likely lead to a positive external impact, on for example the environment. The packaging supports safe transports of batteries going to recycling, thus enabling a resource-efficient way of producing EVBs. It can also help in reducing the number of transport as well as being ergonomic for employees who may handle the packaging with forklifts instead of manual lifts. To further reduce the environmental and social impact, the packaging will be designed to be recyclable and reusable.

4. Empirics

This is the section where findings from the case company is presented, and the thesis focuses more on the specific settings applicable for the company and their packaging situation. The data presented originates from interviews, academic papers and available business data and analyses. It will later be interpreted and analyzed in chapter 5, later resulting in the creation and evaluation of possible design alternatives for packaging solutions. A high-level summary of this section, its structure as well as the key findings, can be seen in Figure 4.1.



4.1 Product Characteristics

Key insights

- EVB differ in dimensions depending on brand and car model
- In Appendix 1, a representative data sample of EVBs validated by the case company is presented
- EV packs are in general larger than PHEV packs

4.2 Mapping Flows

Key insights

- The recycling need occurrs in different steps in the OEMs' processes generating multiple sources for batteries.
- Transportation drives large costs in the recycling operation and can be determining in the business case
- The current packaging solution does not fit the need for the case company and is concidered underdeveloped
- Packaging for modules can be solved by using EUR-pallets and collars, why focus will be more on the solution for packs

4.3 Packaging Requirements

Key insights

- Packaging requirements can be divided into four groups depending on the area they cover. The chategories are supply chain efficiency, environmental impact, regulatory compliance, and business and marketing aspects
- Different stakeholders value the requirements differently

4.4 Market for EVB Recycling

Key insights

- The EVB recycling market is under development, but there is already a high interest from many different parties, creating competition on the market
- EVB recycling market correlates with a delayed distribution to the EV sales market, which also is expected to grow
- The recycling market is expected to have a CAGR of 57% from 2019 to 2030
- Trends on the market are: increasing process innovation, regulations pushing towards increased volumes, and a main challenge is for the OEMs to keep up production to match the demand on the EV market

Figure 4.1. A summary of the key insights from each section in the empirics chapter (source: own illustration)

4.1 Product Characteristics

This section focuses on product characteristics for EVBs and their design variation. Understanding product quality is essential for analyzing product flows for current and future operations. It is also vital to understand if the market is ready for process innovation or not, which is indicated by the level of similarities between EVBs. If the data shows a significant trend towards one specific type of battery when analyzed, it can be assumed that this type of battery is the dominant design on the market and that process innovation therefore will be a major competitive advantage. This is in accordance with the theory presented in *2.2 Supply Chain Theory*. This type of analysis, amongst others, is based on the result of this chapter, and the result will further be used in the flow analysis and the scenario creation.

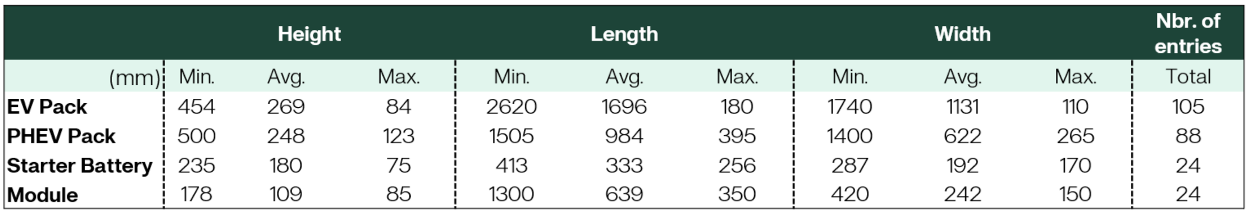
To understand the packaging needs and design requirements, there first needs to be an understanding of the different product characteristics. As disclosed in section *1.1 Background,* the EV battery market is fragmented and has yet to establish a design standard for battery packs, which has led to a vast variation of battery types on the recycling market. To further research this, an extensive list of battery characteristics was gathered, mainly from customer information given to the case company. The list consists of 242 battery types, including packs, modules, and starter batteries, originating from 29 different EV producing entities, presented in *Appendix C: Battery Models*.

Even though the list is extensive, it is not exhaustive. And as expressed in one of the interviews, battery specifications are not always made public, and the market yearns for more information on batteries used, covering the entire battery flora. The reason OEMs hide this information is, according to the interviews, due to commercial interests and a deeply rooted competitiveness that shapes the automotive industry. The secrecy and lack of information makes it difficult to ensure that the result from research is enough to use as a base in an analysis. However, the compiled list presented in *Appendix C: Battery Models* has been validated and assumed to be representative by multiple representatives from the case company. By adopting this assumption of a representative data sample, the list of characteristics can be used to outline market characteristics when it comes to varying dimensions.

As an additional insight into market characteristics, it is worth having in mind that battery dimensions have changed significantly during the last few years and are expected to keep changing in the coming ones as well. This according to interviews with the case company. This indicates a continued variation of dimensions for the foreseeable future. The dimensions also vary between countries, where for example Germany prefers larger battery packs and Italy smaller ones. This is according to an interview with a business analyst at the case company. Nevertheless, representatives from the case company have included these aspects in their evaluation of the list, and the assumption of a representative sample stand.

Finally, the full list presented in *Appendix C: Battery Models* consists, for each battery, of information on the supplier, if it is a pack, module, or starter battery, the battery's weight, as well as its height, length, and width. Where information is missing the cell has been marked with a blank or zero. A summary of the list is presented below in Table 4.1.

Table 4.1. A summary of Appendix C: Battery Models highlighting the nature of the dataset and illustrating the variability of battery qualities.



	Height			Length			Width			Nbr. of entries
(mm)	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Total
EV Pack	454	269	84	2620	1696	180	1740	1131	110	105
PHEV Pack	500	248	123	1505	984	395	1400	622	265	88
Starter Battery	235	180	75	413	333	256	287	192	170	24
Module	178	109	85	1300	639	350	420	242	150	24

4.2 Mapping Process- and Product Flows

Included in Pålsson's framework presented in section *2.3.5. Evaluating Design Performance*, the following section will map the relevant flows and processes. The purpose is to understand the physical flows, where they originate from, how they behave and develop, different challenges in the process steps, how the current market is characterized and what trends will affect it in the future.

4.2.1 Process Flow

This section highlights the relevant processes flow and interaction points for a packaging solution at the case company. The information is mainly based on interviews with the case company, but learnings can be transferred to the general recycling case as well. Insights from this section are later used in the flow analysis and scenario evaluation.

The process flow of the case company is a fundamental component in understanding the needs for a packaging solution and what defines the performance of the solution. Starting in the battery life cycle described in section *2.1.1 EV Battery Life Cycle*, the scope is now narrowed down to the interaction points between the EVB and a packaging solution from the OEM sources. In other words, the focus from hereon will be on a smaller part of the EVB life cycle, zooming in on processes and flows, starting from the different OEM battery sources and ending at the point where the EVBs enters the recycling process, and the packaging material is sent back to the OEM for reuse. Seen in *Figure 4.2* is an illustration of the process flow, based on interviews at the case company. Here, five main sources for batteries sent to recycling were identified.

The need for recycling packs or modules occurs in the OEMs' production, testing and R&D sites, as well as during the use phase of vehicles (mainly crashed and damaged batteries) and when the EVB reaches its EOL. Packs and modules are then transported to a consolidating interim storage and later to the recycling plant where the EVBs are separated from the transport packaging and put into the recycling process. Ideally, reusable packaging is then sent back to the OEM operation. These steps are further described in detail in the sections below, focusing on what handling, volumes, costs, and other parameters required from a packaging solution and how the current processes can be improved with the help of different packaging designs.

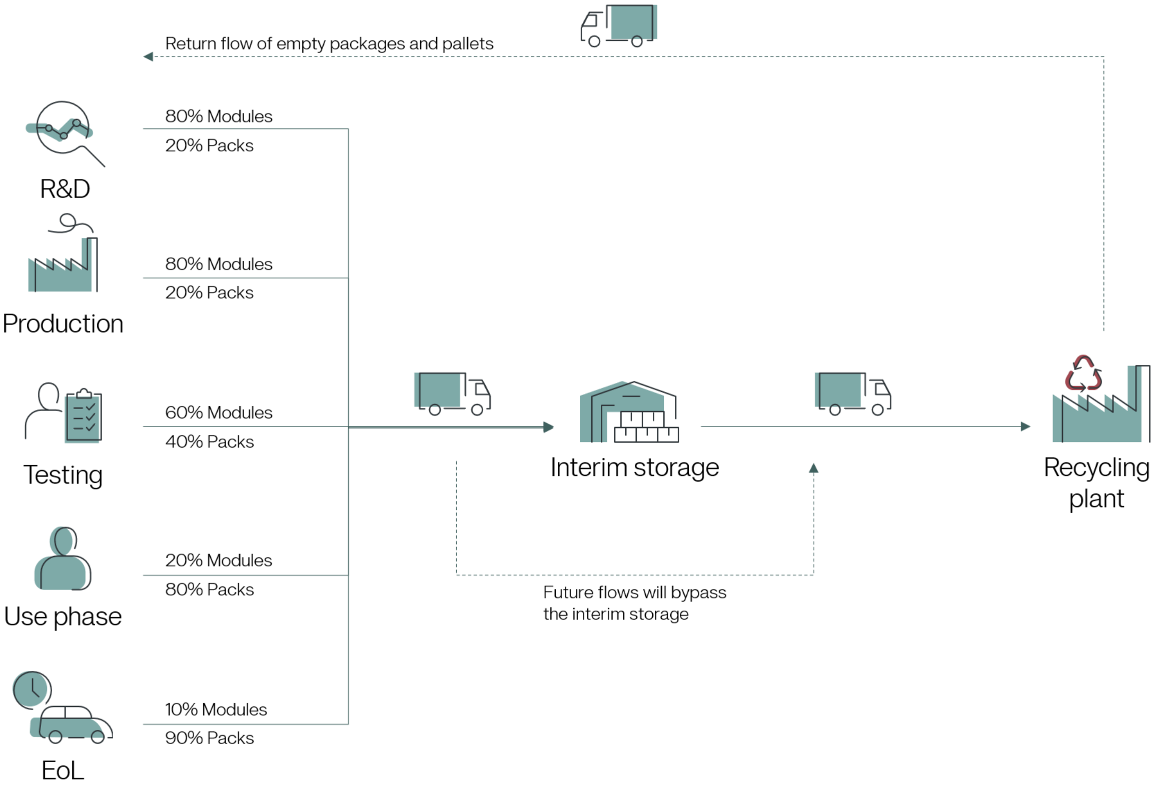


Figure 4.2. Process mapping of battery flows for the case company. The split between modules and packs is highlighted at each source. These numbers are estimates from the case company and are illustrative rather than exact. (Source: own illustration)

OEM Battery Sources

One of the delimitations of this thesis is to only consider battery flows from OEMs, thereby excluding flows from car dealerships, scrap yards, etc. However, from interviews it became obvious that the need for recycling occurred in different steps in the EVB life cycle and that this dictated the characteristics of the material flow going to the recycler. OEM operations are extensive and include multiple processes where batteries can fall out of circulation, which is why it is important to map these sources of EVB and understand their qualities and future development. The origin and characteristics of each OEM recycling will be further explored in this section and are illustrated to the left in *Figure 4.2*. Noteworthy, however, is the similarities in handling requirements for all battery sources. The standard is that a transit packaging solution is used, and that all handling is managed by trucks.

The first source where the need for battery recycling can occur is within the R&D operation. Here, OEMs research and develop their vehicles, testing new setups, models, and components. OEMs' R&D activities mainly result in the recycling of modules rather than packs. Stated in one interview, the reason for this is that their process steps are gradual and that there is usually an opportunity to reuse some of the parts included in a pack, limiting the need for recycling an entire battery pack. An estimate suggests that 80% of volumes are modules and 20% packs. Further, the operation is generally limited to smaller volumes and due to the nature of R&D processes, the expected flow of EVBs going to recyclers is unpredictable. Unpredictability is seen by the case company, and the theory presented in *2.2 Supply Chain Theory*, as a constraining factor when developing a standardized packaging solution. R&D is therefore not predicted to be a primary long-term source of EVBs for recyclers. Nevertheless, because of the current innovation rate on the EV market, recycling needs originating from R&D make up a significant share of the case company's battery sources today. But when production of EVs scales, the share of batteries originating from R&D is projected to decrease.

The second process identified as a EVB source for recyclers is the OEM production, where scrap is the main object of interest. Scrap occurs, as in any production process, when errors make the product unusable and not fit for its purpose or market. It can be due to design deviations, safety issues, new regulations, etc. Using the logic that applies to R&D processes, the main battery type falling out of circulation as scrap is modules. According to an estimate given by the case company, 80% of the batteries sent to recycling from production are modules, and 20% packs. As a result of the still developing production techniques and product designs, the scrap rate of OEMs is relatively high as of now (stated in interview with the case company). With a more standardized and large-scale production the scrap rate is expected to drop. The total volume of scrap is, however, expected to increase due to the nearly exponential volume increase in EV production. By establishing this volume estimate, production scrap is expected to be a major source of batteries in future recycling operations.

The third BEV source identified is OEM testing operations, where OEMs test the performance of their vehicles and components. An example of testing activity is to test an EV's range on a single charge, or to test safety features during a crash. Batteries used in these activities are sent to recycling when the testing is done. The case company estimates that this leads 60% of the batteries to be modules and 40% to be packs. Packs are more common from this source than from example production since OEMs test, and consequently retire, the entire vehicle. The share of batteries from this source is expected to decrease in the future due to increased production and more robust and reliable designs. Testing operations are, however, a noticeable source of batteries for recyclers today.

Fourth, the use phase of an EV can also be seen as a source for OEM originating flows. The need for recycling during the use phase, not to confuse it with EOL, mainly originates from recalls and service activities. Recalling happens when OEMs must take back a batch, or a part of a batch, of cars due to a late-discovered error. During one interview an example was shared where an OEM had to recall, scrap and recycle 3 000 cars, leading to the same number of packs entering the recycling market. Service activities can similarly result in the recalling of smaller parts of the battery. It is estimated that the result of these activities is a battery flow consisting of 80% packs and 20% modules. However, noteworthy is that due to the unpredictable nature of this ad hoc flow, it will most likely not become the main source when robust production standards are established by the OEMs.

Lastly, when an EV reaches its end of life and the SOH is around 80%, it is generally recycled if it is not used for a secondary purpose (Harrison and Theil, 2017). The current volume of EOL on the recycling market is low, due to the lifetime of the EVBs. The batteries coming in today have been in use for approximately 5-10 years and originate from sales on an early EV market. Because of this, the current volumes are low, but expected to increase. The SOH is generally evenly distributed between the modules in the EVB, resulting in most packs being recycled from this source. Therefore, estimates from the case company tell that 90% of the flow from EOL sources are packs, leaving 10% for modules. This source is expected to be one of the main sources for recycled batteries in the future.

Transportation from OEMs and Interim Storage

Transportation is one of the main cost drivers for recycling EV batteries. For EOL batteries, it has been estimated that 40% of the recycling cost is driven by transportation, making it a pivotal factor for the business case of recycling EVBs (Stallery, 2021). Stated in one interview is that the case company is currently transporting, and will continue to transport, batteries by road. This statement was supported with the argument that the planned recycling plant is located within relative proximity to the OEMs as well as the fact that air transport is not allowed for damaged batteries (see *2.1.2 Regulations for Battery Waste Transportation*). Alongside these arguments there is also the cost perspective, where it is logical that the company wants to avoid long distance hauling, often conducted by train, boat or flight.

Transportation contracts vary between the service providers, but in general the case company pays a fixed sum for each full truck load (FTL) shipment. Because of this, as well as the operational efficiency and the environmental aspects, the truck fill rate is of high importance to the case company. However, dealing with a highly variable sourcing situation the difficulty to increase the truck fill rate has been expressed in interviews. One extreme example shared by the case company, which highlights the need for a well-designed packaging solution, was a shipment sent from an OEM consisting of only three packs with a total weight of 3.6 tons in a FTL. By filling the truck this way, a majority of the volume was unused, and 16.4 tons could be added to the shipment before reaching the loading limit. This example illustrates the difficulty to properly fill trucks with goods affected by a varying demand, and as stated in the interview, it also provides a reason to question the transportation contracts as well as the packaging solution.

Dealing with an immature recycling market, the case company has decreased the impact of variating supply by implementing a buffer in the form of an interim storage. The storage collects orders from different suppliers and consolidates them in shipments going to the recycling plant. By using an interim storage close to the OEMs, the case company is able to reduce the kilometers driven by FTLs with low fill rates and can instead use consolidated shipments for longer transportations. Also, given the high complexity of transporting EVBs in accordance with regulations and the economic advantages of bulk shipments, a consolidating storage is viewed as a crucial component in an EOL ecosystem by literature (Stallery, 2021). This increases the total fill rate and gives the company an opportunity to plan a continuous flow of batteries to the recycling plant. The need for consolidation is also expressed by an external supply chain expert and in literature where the need for further research on the topic is highlighted (Stallery, 2021).

As stated in *Figure 4.2*, the interim storage is likely to be excluded from the future flows according to the case company. This is expected to happen when volumes increase to a level where each OEM can supply a steady flow of fully loaded FTLs, and when the packaging solutions are more optimized towards achieving a higher fill rate in the trucks. However, when this change of operations will occur is yet unknown.

Recycling Plant and Return of Packaging Material

When arriving at the recycling plant, the batteries are offloaded from the FTL and stored in the warehouse using a truck. They stay in the warehouse until they enter the recycling process and are separated from the transit packaging - initiated by discharging and later followed by disassembly. Days on hand, storage time, and other warehouse parameters are difficult to predict at the case company since the current operations are not commercial recycling, but rather R&D related. However, as explained by an external supply chain expert, this is an important aspect of building the business case of new packaging solutions since it affects the purchasing of packages as well as the cycle time for the packages. As for the packages, when separated from the batteries, they are stored later to be returned to the OEMs for reuse. If a single use has been used, it is scrapped instead of returned. During this handling process, the warehouse manager expressed that difficulties in handling variation occur due to the vague ADR regulations, the different interpretations of the packaging requirements, as well as the varying types and sizes of batteries.

4.2.2 Product Flow

This section lays the foundation for determining the dimensions of the products that the packaging solution is intended for. These results will later help form packaging designs in the scenario creation section.

Besides understanding the product requirements, a necessary step when designing a packaging solution, as discussed in *2.3 Packaging Theory*, is to understand the target market for which the solution is intended for. In the case of EVBs, the dimensions of the battery packs being recycled is a natural divider of the market. If a packaging solution fits a pack’s given dimensions, it has the potential of capturing that given market share. Additionally, there is a connection between the car model and the pack size. This means that if the car model is known, the pack dimensions can be derived. This is because each car model has only one pack with specific dimensions to that model. For that reason, accumulated sales data for the most sold EV car models (both BEV and PHEV) over the period 2019-2022 has been collected (Jato, 2022; CarSalesBase, 2020; CarSalesBase, 2022). Using sales on the EV market, connecting it to the battery dimensions, creates a weighted list over the battery sizes most likely to be recycled. This is done in section *5.1 Flow Analysis*, and the information can then be used to determine the potential market capture of the suggested packaging solutions.

All sales data is presented in *Appendix B: Most Sold EVs*, while this section provides the key takeaways. In total, sales data was gathered for 135 unique EV car models, where the split between BEV and PHEV models was 77 respectively 58 models. The sales data is collected from several organizations and institutions who gather statistics regarding the car industry (Jato, 2022; CarSalesBase, 2020; CarSalesBase, 2022). Due to the lack of exhaustive data, the study is based on only publicly available data covering 86% of the most sold cars during 2019-2022 (having information for 5 750 000 of the 6 700 000 sold EVs). Even though the data does not cover every car sold, the percentage is relatively high and provides valuable insights for the packaging design according to the case company. *Table 4.2* provides an overview of the 10 most sold car models and groups the rest of the models where sales data is known into the group called “Others”. The models where sales data is missing are labeled “Missing data”. As seen in *table 4.2* a total of approximately 6 700 000 EVs have been sold during the years 2019-2022. What was also discovered when exploring the data was that the sales from BEV models were more concentrated to a few models, whilst the sales for the PHEV models were distributed over more models. For BEVs the top 15 most sold models stood for almost 62% of the sales whereas the same Figure for PHEVs was 49%.

Table 4.2: Overview of the most sold car models in Europe, accumulated over the period 2019-2022 (Jato, 2022; CarSalesBase, 2020; CarSalesBase, 2022).

Ranking	Units sold	BEV/PHEV
1	413 500	BEV
2	249 400	BEV
3	180 900	BEV
4	164 700	BEV
5	145 700	BEV
6	126 900	PHEV
7	126 600	BEV
8	126 100	BEV
9	125 600	BEV
10	120 500	BEV
Others	**3 983 200**	
Missing data	**932 200**	
Total sold	**6 695 200**	

4.2.3 Current Packaging Solution

This section includes a description of the current packaging and logistics solution experienced by the case company. This information is a summary of interviews with representatives from the case company and will further be used to define evaluation criteria for the suggested packaging solution.

Investigating the current packaging solutions used by OEMs, the lack of standardization is obvious. Transit packaging for battery packs ranges from large metal cages with integrated sprinkler systems to simple EUR-pallets. And for modules, the transit packaging can be anything from a specially designed plastic box with inserts to a pallet with collars filled with heat ulcer for isolation and protection. This was made clear when visiting the case company's warehouse where the site manager and warehouse manager were interviewed. They both expressed the difficulty experienced from handling differences in packaging solutions and how OEMs interpreted packaging requirements very differently.

"Some packs arrive on too small pallets, and we need to re-pack them to avoid a dangerous storage situation that could lead to damaged or scrapped goods."

- Quote from the warehouse manager

Starting with the variation, it is established in section *4.1 Product Characteristics* that the batteries vary widely in type, size, and weight. This logically leads to differing packaging needs and an inherited variation for the packaging solutions. A flat and large pack obviously has different requirements on the packaging solution than a small cubical hybrid battery pack. In addition to the varying shapes, batteries coming into the recycling cycle are in different conditions having different SOH. A battery classified as red, severely damaged, has more stringent safety requirements than a green battery without any damage, in accordance with *2.1.2 Regulations for Battery Waste Transportation*. To standardize packaging solutions across the different conditions, the OEMs together with packaging producers have generally designed solutions that take height for red batteries. This makes one interviewee argue that the solutions on the market for packaging solutions today are heavily over engineered and that there is a market opportunity for packaging solutions targeting only green and yellow batteries, with light to no damage. Further, during interviews it became clear that it is the OEMs that own and take responsibility for the packaging designs and solutions. Given that OEMs in the automotive industry historically avoid collaborations and cross company standards, this leads to an additional variability of design.

Another interesting finding when looking at the current solution is the regulatory and functional requirements applied to the packaging material. First of all, multiple interviewees state that the ADR regulations presented in section *2.1.2 Regulation for Battery Waste Transportation* are vague and that OEMs and transporters treat them very differently. One example is the rule stating that modules can be consolidated in the same transit packaging if they have a separate secondary packaging layer. One shipper addressed this by putting each module in a zip-bag and then in a larger crate while another shipper used customized inserts for each module. Both solutions follow the ADR regulation, but obviously live up to different standards. Interviewees argue that this ambiguity has its root in the fact that EVB recycling is a relatively new market and that the regulatory aspects are lagging. Second, the handling process differs between OEMs, leading to further requirements for packaging solutions. An example of this was shared in an interview, where one shipper had stored the EVBs outside in wooden crates. The crates are efficient in the sense that they have standardized sizes and are stackable. However, by storing them outside the shipper exposed them to rain resulting in a mold layer on the lid of the crates. Another example was visualized during the site visit when the warehouse manager described how they regularly needed to repack some batteries due to other storing standards. The example was a pack arriving on EUR pallets (1200 x 800 mm) where the packs had almost double dimensions. The shipper had no problem shipping the packs on EUR pallets, but when it arrived at the warehouse, they deemed it dangerous to handle and had to switch to a larger pallet for better balance. These examples represent how handling routines specific to a shipper lead to an increased number of requirements and aspects to include in an improved packaging solution.

Lastly, the representatives from the case company have identified a discrepancy between their contract with the haulage and their contract with the OEMs. The case company generally pays the haulage per FTL, regardless of the weight and size of the cargo. On the other hand, OEMs pay the case company only for the transported weight, or number of EVBs. Combining this with the fact that the OEMs oversee the packaging solution, the interviewees have identified a potential misalignment of incentives between the case company and the OEMs. Naturally, by paying per FTL, the case company wants to maximize the fill rate of the trucks to share the transportation cost on as many EVBs as possible. They want packaging solutions to be stackable, foldable, and as standardized as possible. This is not the goal for OEMs. Their concerns lie in getting rid of the EVBs to have an efficient operation and keep storage and handling costs down. Their needs for packaging solutions are instead that they are cost effective, can be loaded quickly, but most important of all is that EVBs leave their site at as high frequency as possible. This misalignment can in theory lead to an unprofitable operation for a battery recycler, which worsens the business case for recycling EVBs.

4.2.4 Future Packaging Solutions for Modules

During the interviews and data collection, it became clear that packs were the main challenge when developing the packaging solutions. This is because of the large dimensions of the packs, compared to modules. The pack dimensions limit the possibility of fitting multiple packs in the same transit packaging, it also limits the handling and storing prospects. In contrast, modules can be packed together, and are easier to manage and store in groups. Therefore, the focus for the thesis will be to find an improved packaging solution for the packs, that could potentially also fit modules.

However, there are improvements to be made when it comes to packaging solutions for modules. In parallel to the thesis, representatives from the case company have been investigating how a solution for the modules can be designed. As of May 2023, the most prominent solution is to use an EUR-pallet with wooden collars and inserts to separate the modules. This solution benefits from the standardized EUR-pallet design, making it accessible and relatively cheap to use. It has also been accepted by the case company's ADR expert and thereby follows the EU regulation for transport of dangerous goods. *Figure 4.3* illustrates the idea of this solution. By implementing the EUR-pallet with inserts and collar, the modules can be efficiently managed, and focus can shift towards the packs. In addition, the solution is flexible with regards to the use of collars - it can be adjusted in height by using one, two or three collars. The collars are also detachable and foldable, minimizing the needed storage space when the packaging is not used.

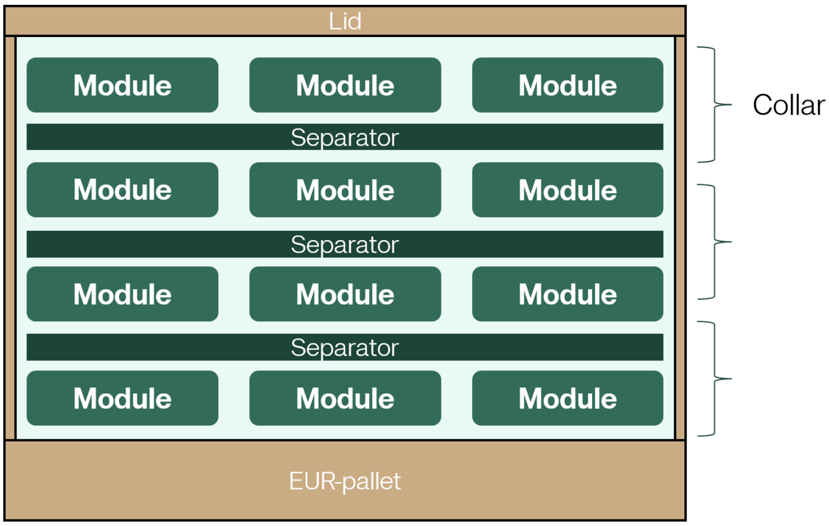


Figure 4.3. Illustration of the packaging solution suggested for modules. In the best case it will pack 12 modules using 3 pallet collars. (Source: own illustration)

4.3 Packaging Requirements

An important step in developing a packaging solution for transport is to identify what requirements are applicable, both from the stakeholders involved as well as from the supply chain activities it will go through. Based on interviews and by reviewing literature, relevant stakeholders to consider when transporting batteries are the battery itself, the battery recycler, the OEMs, the packaging supplier, the regulatory enforcer, the transporter and the environment. The stakeholders all pose their requirements on the packaging solution. These were divided into four categories from Silva and Pålsson's (2022) list on requirements for industrial packaging:

1. Supply Chain Efficiency
2. Environmental Impact
3. Regulatory Compliance

4. Business/Marketing Aspects

Findings from a workshop about important packaging features and interviews at the case company are summarized under these four categories below.

Supply Chain Efficiency
Requirements regarding supply chain efficiency are posed by stakeholders involved in the handling of the package. In the case of recycling batteries these are the battery recycler, the OEMs, and the transporter. It should also be kept in mind that supply chain efficiency is tightly connected to environmental impact which is why the environment can be seen as a stakeholder posing requirements on the solution.

The main idea of achieving supply chain efficiency is to have a smooth flow of packages where the packaging design facilitates the handling. Therefore, a primary requirement mentioned was handling efficiency where the packaging design must be compatible with trucks, storing racks and handling equipment at each stakeholders' site. An important step here is the transportation and storage where the size of the package should fit the dimensions of a truck or a rack system. Other aspects highlighted in relation to the transport were stackability to utilize the height of the truck and using light weight material to add as little extra weight. To better utilize the empty transport going to the OEMs, another requirement mentioned was a foldable design which would enable shipping more EVBs and less air. After a package arrives at the battery recycler's site carrying a charged battery it will at some point interact with other activities in the recycling process. Hence a soft requirement mentioned was the compatibility with other process steps in other processes where the design for example could be used when discharging the battery or be used as a carrier along the recycling process. Another mentioned aspect is the ease of cleaning and maintaining the package.

As previously concluded, the package is aimed to fit a variety of products with different dimensions and shapes. It is therefore crucial that the design is flexible to fit different product dimensions, rather than having a packaging solution specific to each battery dimension. This relates to the idea of standardization where interviewees at the case company mentioned that the unified solution should be able to fit as many products as possible. In these discussions a concept highlighted was modular design which would enable a flexible design while still having a standardized design.

Finally, the supply chain connects several stakeholders, leading to the importance of keeping everyone up to date with information. One way to achieve this is by implementing traceability into the solution which gives information on where the package is located which can be necessary both when planning but also when tracking a lost package. Thus, the package should optimally be designed with track and trace compatibility in mind. Having technology in mind, another feature mentioned was to make the design compatible for automation since the OEM sites often are automated to a large extent.

Automation would therefore both be beneficial both from a supply chain efficiency perspective, but also as a selling point.

Environmental Impact

In the production phase of the package, it was highlighted that the material and colors going into the package should be carefully chosen. This is due to the environmental impact of different materials but also the material durability which will impact the lifetime. Packaging material must comply with regulations, for example to exclude hazardous substances when producing a plastic container. The packaging material will also impact the weather and water resistance which is another aspect influencing the lifetime of the package. The case company for example mentioned one example where a wooden box had been used where mold had started to grow since the package stood in a wet environment.

Another key requirement highlighted during the interviews was that the package should be reusable. This is mainly to reduce the environmental impact but also to reduce the amount of waste produced. Lastly, the package should be recyclable after serving its purpose which is influenced by the material used when producing it.

Regulatory Compliance

Another important category for industrial packages is compliance with regulations. It is not only regulatory enforcers who are concerned about safety precautions and regulatory compliance. In the case of battery recycling, they are regulated by ADR to achieve safe transportation where sufficient safety measures are taken. Another aspect that must be incorporated is to label the package with signs informing that it contains dangerous goods.

Business/Marketing Aspects

Lastly, a fourth category has been added to adapt Pålsson’s list to this study. One business-related requirement is that the package should be affordable for the stakeholder owning the solution, no matter whether it is the recycler or the transporter. At the same time, it should also be compatible with the customers’ lines. An example of this was mentioned previously with automation, which can be seen as a selling point towards the OEMs. Another highlighted aspect for the owning company is branding where its logotype is displayed on the package for marketing reasons.

4.4 Market for EVB Recycling

This section covers topics associated with the market for EVB recycling. It focuses on the different stakeholders creating a competitive environment, the future growth estimates, and the most prominent market. These results will in later chapters be included in the scenario creation and evaluation.

4.4.1 Market Mapping

When understanding an industry, it is important to identify stakeholders involved, which can be done by mapping them to steps in the supply chain (Pålsson, pp. 27-42, 2018). BloombergNEF (2022) has done such an investigation on the European market for battery recycling which is illustrated in *Figure 4.4*. However, it should be noted that this process map does not include every active stakeholder but highlights a handful of strategic collaborations and joint ventures.

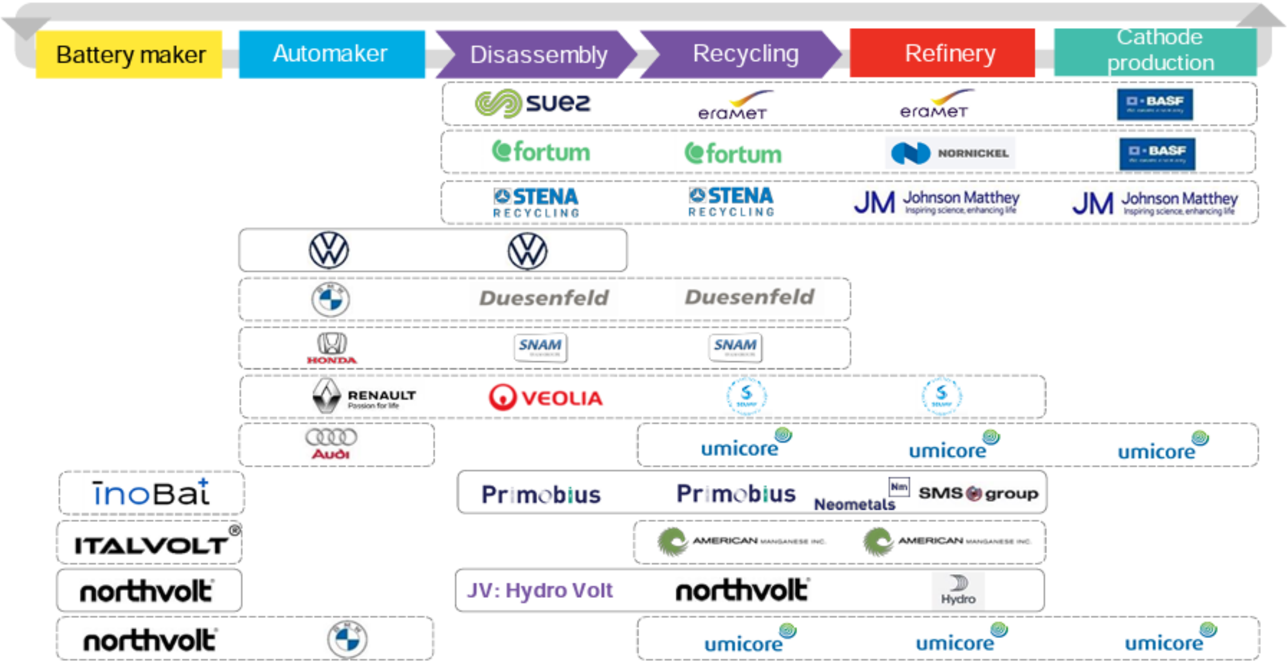


Figure 4.4: The supply chain for the battery recycling industry provides examples of stakeholders involved in each step. Note: the solid gray line indicates joint ventures and in-house operations. The dotted lines indicate strategic cooperation. (Source: BloombergNEF, 2022)

As the figure indicates, the European battery recycling market is competitive with multiple stakeholders and collaborations involved. This can partly be seen by the large number of players in each step, but also by the fact that there are even more organizations active on the European market such as EUCBAT, EBRA, Accurec Recycling to mention a few (Recharge, 2023). Another indication is that competition comes from different directions. Recyclers compete both with players already active in recycling, such as Stena Recycling, but also with OEMs and cathode producers changing the way they operate. A few years ago, OEMs bought their batteries from large Asian battery producers but during the last couple of years many stakeholders have realized the value of controlling the whole or large parts of the supply chain (Blue Institute, 2022). One idea with the activity integration is to secure access to raw material for the batteries which is why there are examples of OEMs integrating activities both within mining and within battery recycling. Competition might also come from repurposing where second-life applications for batteries is a subject that is gaining more attention, both from researchers and companies (McKinsey, 2019; Melin, 2019). If the collection for second life repurposing of batteries reaches higher levels it might also contribute to making the resource sourcing more competitive for battery recyclers.

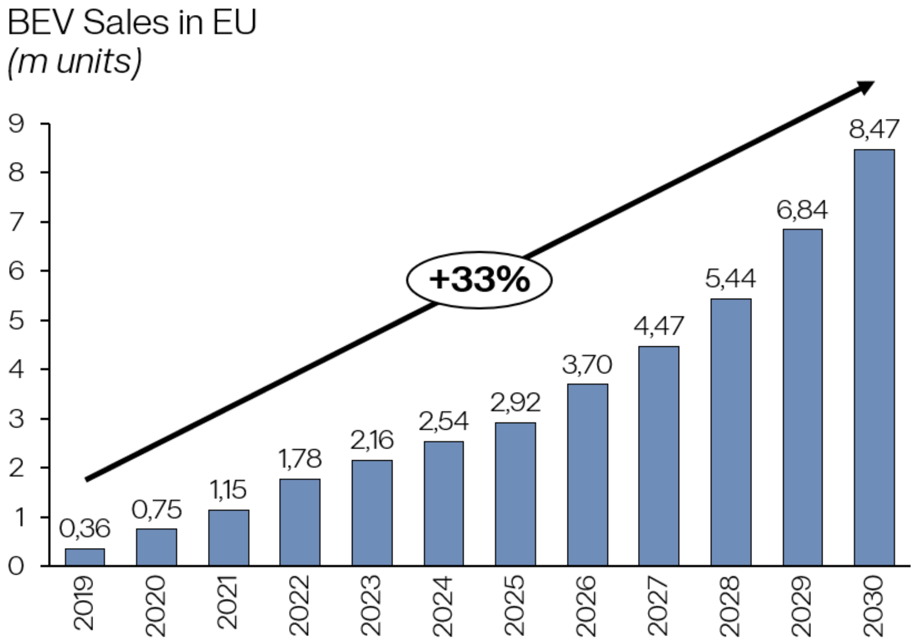
4.4.2 Future Market Growth Estimates

The recycling market has rapidly grown in recent years and estimates suggest a continuous volume increase. When evaluating the potential benefits of a unified packaging solution this growth has to be accounted for. Therefore, this chapter outlines an estimate of the future market growth. The result will later be used to analyze and evaluate different packaging solutions.

As explained in section *1.1. Background* and in *4.2.1. Process Flow*, the recycling market for EVBs is heavily dependent on the EV market (Harrison and Theil, 2017). Therefore, understanding the future of the EV market is vital in estimating the future EVB recycling market. This section accounts for future market estimates for the EV market, how they correlate to the EVB recycling market, and finally an estimate of the future EVB market is presented.

The worldwide EV market has an expected CAGR of 32.2% from 2017 to 2027, and Europe is further driving the market boom with a 39.0% CAGR during the same time period (Statista, 2022). The CAGR suggests a strong development on the market, doubling it 25 times during a 10-year period. This is further supported by sales estimates, where Forbes estimates the 2030 sales to 10.9 million vehicles sold (compared to 2.1 million in 2022), IEA estimates 13.3 million vehicles sold the same year (Forbes, 2023; IEA, 2022). And as previously mentioned the European Union will enforce an emissions cap on the vehicle market, further increasing the interest in EVs. In their report, Harrison and Theil connect the sales estimates and the recycling market by incorporating the EVB life time stages of the EVB life cycle together with the future market growth estimates (Harrison and Theil, 2017). Basing the forecast for the recycling market on EV sales results in a distribution delayed forecasting model. The authors conclude that the recycling market will continue to grow, and after 2030 they forecast a steeper increase in the market growth, describing it as exponential. This growth, and the relation between EV sales and the recycling market, is further confirmed in an interview with a business developer at the case company. “The relation between the EV sales market and the recycling market for EVBs can be described as a double-s curve” she states in an interview. Another interviewee describes the future market growth as an “iceberg of batteries they need to manage” and at the same time ensure taking an as large as possible market share of.

With this background, *Figure 4.5* compares the estimated future market growth for EV sales and the estimated recycling market for EVBs. Here, the double-s curve can be observed, and the estimates suggest a CAGR of 57% for the recycling market for the time period 2019 to 2030.



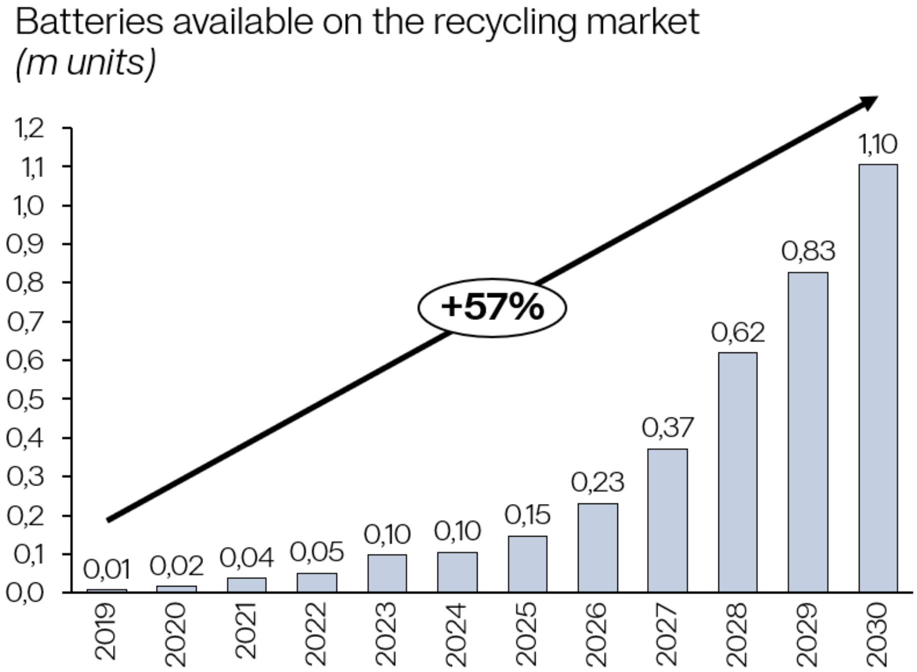


Figure 4.5. Sales forecast (number of vehicles) for the European BEV market (upper graph) and the estimated number of batteries available on the recycling market (lower graph). Observe the different scales on the y-axis. (Source: own illustration of Morgan Stanley; Statista; European Commission).

4.4.3 EV Market Trends

This section presents future market trends for the EV market, focusing on aspects relevant only for the EVB recycling process. The market trends indicate how characteristics of the future EVB flows will develop. Insights presented in this section will later be used to estimate future market volumes and characteristics, as well as evaluate the validity and performance of the different solution scenarios.

As shown in section *4.4.2 Future Market Growth Estimates*, EVB recycling heavily relies on the EV market and its development. Therefore, this section covers a collection of prominent market trends discovered in interviews and literature. Generally, the EV market is closing in on a design standard leading to an increased need of process innovation, regulatory constraints are pushing OEMs to electrify their fleet faster, and a main challenge for the OEMs is to keep up with supply, where recycling plays a big part.

First, investigating the design trends for new EVBs, a business analyst at the case company expressed the decreasing variation in sizes and dimensions for battery packs. Going back ten years in time, the market design was significantly more fragmented and today, she argues, a design standard or dominant design is on the verge of being established. This phenomenon will be further analyzed in section *5.1.1 Product Categorization*, but figures suggest that a dominant design is emerging when comparing the different sizes of battery packs. Reconnecting to Abernathy and Utterback's phases of innovation (see *2.2 Supply Chain Theory*), interviewees from the case company highlight the need for increased efficiency and process innovation, further strengthening the argument that the product innovation is stabilizing. However, even though the shape of the battery pack design is stabilizing, a trend towards larger battery packs has been observed by the case company. This is argued in interviews to be a result of the improved performance and driving range seen in recent years (IEA, 2022).

Second, the stricter EU regulation for vehicle emissions is increasing the risk for OEMs to produce and cell PHEVs. From the *Fit for 55* agenda, the emission regulations for vehicles has become more strict with regards to CO2 emissions (EU, 2023). This change of regulations, combined with the 100% reduction of emission in 2035, has led to a decrease in sales for PHEVs, and estimates of future sales are following the same trend (EAFO, 2022; Morgan Stanley, 2021). Relating to the recycling market, there are still many PHEVs being sold and currently active in the fleet. Due to the lifespan of EVBs in general and PHEVs specifically in this case, the recyclers expect the out phasing of PHEVs to affect them only when looking at long term future flows. For shorter terms they instead expect an increase in the total number of recycled PHEV packs, which was expressed in one of the interviews.

Lastly, a prominent challenge of the future EV market is the shortage of supply when it comes to raw material (Morgan Stanley, 2021). Here recycling of EVBs will be an absolute necessity to meet the market demand for EV sales and production. In the report, the risk for a market wide shortage is expressed, and Bloomberg has identified an increase in the commodity price for raw material because of this (Volta Battery, 2022). Further, in interviews with the case company, they express the urgency of efficient sourcing of batteries for recycling and plan to source as much material as possible in the coming years.

4.5 Summary

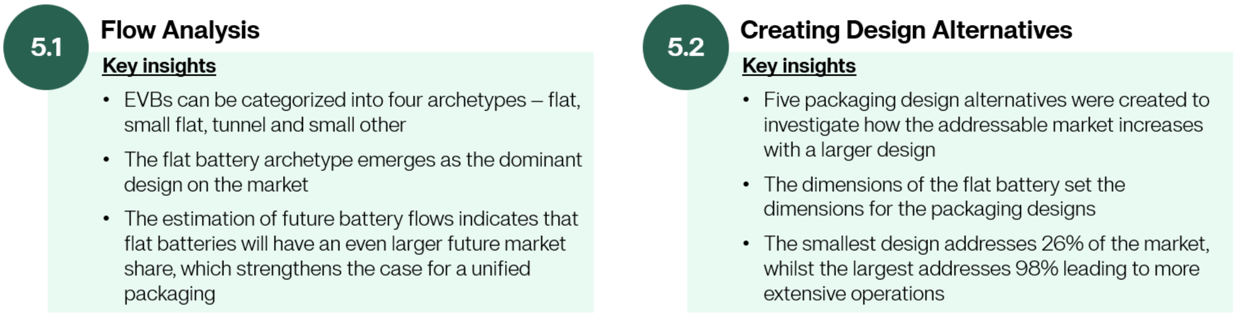
When summarizing the empirics, the business aspects of a unified packaging solution seem attractive. Even though it was concluded that there is a variety in battery sizes and sources, the growing EV volumes indicate an increasing need for a functioning recycling system. The growing volumes and lack of a standardized solution also highlights the potential for a unified packaging and logistics solution. Through interviews it became clear that the currently available packaging solutions are not well-designed, which leaves large efficiency gains for a unified solution.

A next step for a battery recycler would then be to analyze the battery flows to design a packaging system that captures this valuable source of material. In addition to this analysis, it is important to keep the requirements mentioned in *4.3 Packaging Requirements* in mind when designing the system. This is to ensure a high supply chain efficiency, but also that the packaging is compliant with regulations. Lastly the section mentions a couple of optional packaging features, related to the environment and business aspects, that can be added to the design, making it more attractive compared to other solutions.

A final reminder, before diving into the analysis, is that the focus will be on battery packs henceforth, not investigating a packaging solution for modules. In the empirics section it was concluded that the case company is already working on a solution for modules. Additionally, the packs themselves are bigger than the modules, meaning that they set the maximal dimensions for the packaging solution. Meaning that a well-designed solution for packs has the potential to transport modules as well. There is also a lack of data for module dimensions and modules per battery pack design which aggravates further analysis.

5. Analysis

Based on the findings from the previous chapters, this chapter combines findings and analyzes the current and future flow of material, as well as its characteristics. The analysis also presents five different design alternatives based on the difference in their addressed market shares. The operational performance of these design alternatives is then analyzed to create an understanding of how these packaging solutions not only should be seen as battery crates, but as vital components affecting the entire supply chain. A high-level summary of this section, its structure as well as the key findings, can be seen in Figure 5.1.



5.1 **Flow Analysis**

Key insights

- EVBs can be categorized into four archetypes – flat, small flat, tunnel and small other
- The flat battery archetype emerges as the dominant design on the market
- The estimation of future battery flows indicates that flat batteries will have an even larger future market share, which strengthens the case for a unified packaging

5.2 **Creating Design Alternatives**

Key insights

- Five packaging design alternatives were created to investigate how the addressable market increases with a larger design
- The dimensions of the flat battery set the dimensions for the packaging designs
- The smallest design addresses 26% of the market, whilst the largest addresses 98% leading to more extensive operations

Figure 5.1. A summary of the key insights from each section in the analysis chapter. (Source: own illustration)

5.1 Flow Analysis

In this section of the report the EVBs are connected to market volumes to see how sizes are distributed. To manage the variability, different battery archetypes are created and their likelihood of occurring on the market is estimated. The analysis also incorporates the future market growth estimates and how the archetypes are affected by it.

5.1.1 Product Categorization

As described in *2.2 Supply Chain Theory*, one of Persson’s (1995) principles states that a useful tool when improving a supply chain is differentiation. Therefore, in the case of designing a packaging solution for EVBs, it is helpful to identify similar sizes and features within the battery sample presented in *Appendix C: Battery Models*, and group them into subgroups. Categorizing EVBs into subgroups, referred to as archetypes, facilitates the later process of finding suitable dimensions for a packaging solution. It also facilitates a more comprehensive understanding of an otherwise fragmented market.

From the EVB data gathered, four archetypes are created - called flat, small flat, tunnel and small other - which were identified when going through the dataset of batteries where similar sizes were grouped together. The archetypes are confirmed to be representative for the EVB market according to the case company. An illustration of the four archetypes and their dimensions are presented in *Figure 5.2* below.

	Flat	Small flat	Tunnel	Small other
Length	>= 1000	< 1000	>= 1000	< 1000
Width	>= 800	>= 500	<= 800	< 550
Height	<= 450	<= 380	> 100	< 460

Figure 5.2: The four battery archetypes and their length, width, and height. (Own illustration)

The archetypes are used to group the 145 EVB models in *Appendix C: Battery Models*. *Figure 5.1* shows the distribution between the archetypes as well as the minimal and maximal measures for each dimension and archetype. Note that the original data sample is not connected to any sales figures, meaning that the percentage presented in the figure is not related to the occurrence on the market, but to the relative share in the data set.

Table 5.1: The distribution between battery archetypes for a sample of 145 EVB models when not considering any frequency on the market. Also seen are the max and min dimensions for each archetype.

	Flat		Small flat		Tunnel		Small other	
	Max	Min	Max	Min	Max	Min	Max	Min
Length (mm)	2620	1004	990	705	1511	1020	940	180
Width (mm)	1740	810	830	500	750	305	577	110
Height (mm)	454	110	379	200	500	123	460	84
Battery models (units)	74		27		27		17	
Percentage	51 %		19 %		19 %		11 %	

Figure 5.1 indicates that flat batteries are most common with 51% of the sample, and when combined with the small flat batteries they stand for a share of approximately 70%. What can also be seen is that a packaging solution designed to fit the largest flat batteries would with small adjustments fit all other types, except the largest tunnel batteries where the height exceeds the packaging limitation. The ability to fit many different pack types into one solution is a benefit. However, the risk with having a large packaging design is that it could lead to a low fill rate within the packaging unit when smaller batteries are packed. This needs to be considered when designing the package, as discussed in section *2.3 Packaging Theory*. One way to work around this fill rate problem is to fit more than one pack into the packaging unit when possible. If the packs have an outer shell weighing less than 12 kilograms, the joint packing has to be accompanied by inserts and dividers to follow the ADR regulations. This solution is further discussed in chapter *6.1.3 Cost Comparison Using Joint Packing*. Another way of increasing flexibility of the solution, also discussed in the same theory section, is to design a packaging solution with adjustable height, aiming to address a larger market share and reduce the total volume when possible. An adjustable height together with a packaging solution that can fit multiple packs will be flexible and responsive to variations in battery dimensions. It is also a great tool for improving the fill rate in accordance with 2.3.3 *Standardization and Modularity*.

5.1.2 Market Volumes

As stated, the markets for EVs and EVB recycling are intertwined. Because of this relation, it is possible to categorize the battery dimensions most likely to occur by projecting the archetypes on the batteries found in the sales data. Therefore, in this part, the sales data for the most sold EVs during 2019-2022, presented in *Appendix B: Most Sold EVs*, is expanded with the battery dimensions for each car model. This analysis aims to visualize the distribution of battery sizes on the current EV market.

Table 5.2 shows the distribution when the archetypes are applied to the batteries in the most sold cars during 2019-2022. In *table 5.2* this distribution is also compared to the distribution for the battery sample in *Appendix C - Battery Models*, earlier presented in *table 5.1*.

Table 5.2: Comparison of the distribution between the archetypes for the batteries in the 134 most sold EVs during 2019-2022 and the battery sample presented in Appendix C: Battery Models. EVBs marked N/A in the appendix are here excluded, and their weight has been redistributed to the other batteries.

		Flat	**Small flat**	**Tunnel**	**Small other**
Top sold models	Nbr of models	82	30	14	9
	Percentage	61%	22%	10%	7%
All batteries	Nbr of models	74	27	27	17
	Percentage	51%	19%	19%	11%

Note from *table 5.2*, that when analyzing the most frequent batteries on the EV market, the distribution of archetypes shows a pattern like the distribution based on *Appendix C: Battery Models*. The market is dominated by flat EVBs. This strengthens the reason to design the packaging solution modeled after the flat packs. These findings will be the start when later creating different design alternatives for the packaging solution. Also, by knowing the battery dimensions on the market, it is possible to estimate what share of the market that a packaging design could address by seeing what batteries would fit in it.

In addition, the large representation of flat batteries indicates that the EV market is closing in on a design standard. Connecting this to the theory from *2.2 Supply Chain Theory* it indicates that, according to traditional market development presented by Abernathy and Utterback (1979), the competition will be less based on product innovation, but instead on process innovation. Designing a unified packaging solution is a perfect example of process innovation, and it can therefore be concluded that the timing of launching such a project is good.

5.1.3 Estimated Future Flows

Now focusing on the future flows and volumes on the EVB market, the novelty and uncertainty of the market makes it difficult to determine what batteries will be recycled in the future. However, with the help of market predictions, forecasts from the case company and knowledge about the lifespan of an EVB it is possible to roughly estimate both the total amount of batteries going to recycling, as well as their dimensions. This will be further explained and investigated in this chapter.

EVBs are estimated to have a lifespan of 5-15 years, meaning that most of the batteries on today’s market will reach their EOL and be recycled when getting closer to 2030. Thus, the distribution presented in *table 5.2* gives a hint of what dimension a packaging solution needs to handle in 5-15 years. However, it does not cover the time from now until these EVs reach their EOL.

To estimate the current market distribution, a kind of worst case can be set as a base line. The worst case, for a unified packaging solution, is a market with high product variability. This is best mimicked by distributing the market shares evenly between all variations of battery types. By doing so, all battery types in *Appendix C: Battery Models* have the same likelihood of being sourced, creating uncertainty in the sourcing situation. In contrast, the best case observed is the scenario where sourced batteries have similar dimensions. The best-known case like this is when the market shares are distributed according to the sales data from the most sold EVs 2019 to 2022. Note that when evaluating the best-case distribution of battery types, some batteries lack data on their dimensions, and cannot be assigned to an archetype. To fill this gap, these batteries are categorized using the same market shares calculated from the batteries with known dimensions.

By these observations, a best and worst case can be established, and they are illustrated by the green and red lines respectively in *Figure 5.3*. The third scenario presented, in yellow, is a combined scenario where the market for 2023 is estimated using the worst case, and 2030 using the best case. From 2023 to 2030, the market share for flat batteries is linearly increasing. This is based on the logic that the EVs sold today most likely will be recycled 2030. The use of this projection is beneficial to the business aspects of a unified packaging solution since it starts 2023 by using the worst-case estimate, thereby implementing a type of performance buffer. As for the total market volumes, estimates from Morgan Stanley (2021) are used to establish the market size, represented in *Figure 5.3* by the green dotted line.

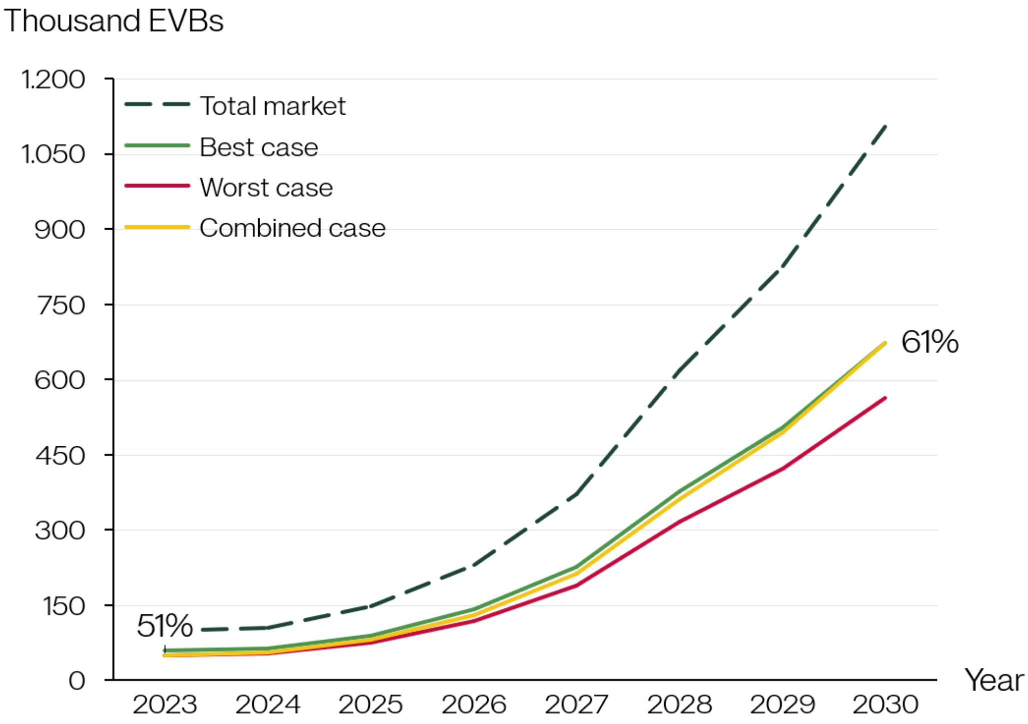


Figure 5.3: A representation of the estimated market share of flat batteries being recycled between 2023-2030. The percentages highlighted in 2023 and 2030 are the market share estimates for the combined case. (Own illustration; Statista 2022)

The worst case sets the lower extreme. However, it is unlikely to occur since the scenario describes a situation where every unique battery type is weighted equally and does not consider the fact that flat batteries are more common than the other archetypes on the market. In discussion with the case company, they agree that this worst case is unlikely to happen. If this scenario was true, it would be difficult for a battery recycler to motivate a packaging design intended for flat batteries since they represent only 50% of the market volume. Further, on the other extreme, the best case is probably not a perfect description either. That is because EVBs have a lifespan of 5-15 years, making it unlikely for a battery sold in an EV 2021 to surface on the recycling market 2023. It therefore seems unlikely that the best-case scenario is representative of today’s market. Nonetheless, the best case seems like a good description of future battery dimensions since the batteries used in today’s most sold cars give a prediction of what will be recycled in 5-15 years. And the worst case is the closest estimate to the current market based on the given data. This is why the combined case, where the best and worst case are combined, appears as a more likely scenario for the future market growth estimates.

Approaching different market estimates using a combined case will also be applied in later analysis when estimating the market share for a specific packaging design. With the same approach, the 2023 market share will be represented by a scenario using *Appendix C: Battery Models*, and the 2030 market share will be represented by estimates based on *Appendix B: Most Sold EV’s*. Estimating the years in between, a linear scaling of the market share will be applied.

The findings in this subchapter complement the previous findings which made it possible to see what share of the market that a packaging design can address. The market share for a given packaging unit will be a product of the number of EVBs captured by the design inner dimensions, and their relative market share. Further, this analysis concludes two things, first being that by comparing the two different market share estimates, a realistic case can be found by combining the two scenarios. Second, flat batteries will likely increase in market share, indicating that they are becoming the dominant design for EVBs. With this established, the design for a packaging solution will most likely benefit from mimicking the design of a flat pack. In the coming chapters, the flat design will be seen as a status quo, and the design alternatives later developed are based on the proportions of a flat pack.

5.1.4 Operational Model

As stated, with the insights gained from previous analyses, it is possible to estimate the addressable market for a given packaging design, as well as its resulting operational setup. These findings will be used to build a financial model to evaluate the designs. An Excel model for packaging performance and its operational implication for a battery recycler is used for this purpose. In short, the model takes packaging design dimensions (length, width, and height) as input and gives the operational outputs that the design would implicate, such as the captured market volume, transport fill rate, warehouse area needed and number of FTEs (Full Time Equivalent). The estimates cover operations from 2023 to 2030. Thus, the model relates a packaging design to the main operational effects implementation would lead to. A full overview of the model, its outputs and the logic used to create it is presented below, and later summarized in *table 5.3*.

The first operational parameter presented in *table 5.3* is the total volume that the packaging design addresses, measured in battery units from the European EVB recycling market. The number represents all battery units that could potentially be packed using the packaging design. To estimate this, EVBs able to fit within the packaging dimensions are connected to their respective market share estimate. This share is then multiplied with the total number of battery units on the market which is given by dividing the total weight of batteries going to recycling according to a Morgan Stanley report (2021) with the average battery weight in the dataset, see *equation (5.1)*. The next output is the captured volume, measured in battery units, and is closely related to the volume being addressed, but refers to the number of units captured by the battery recycler. The figure is estimated by multiplying the addressed volume with an estimated market share and a customer acceptance rate, which are set to 30% and 75% respectively. The customer acceptance rate refers to the rate of customers buying into the packaging solution. In other words, the customer acceptance rate means that some customers are not willing to use the new solution, even though their EVBs are addressable. By considering these two factors, the result is the estimated number of batteries that a given packaging design will capture, see *equation (5.2)*.

$$(5.1)\ Addressed\ market = Total\ market \cdot Share\ of\ EVBs\ fitting\ the\ packaging\ (\%)$$

$$(5.2)$$
$$Captured\ volume = Addressed\ market \cdot Market\ share\ (\%)\ \cdot Customer\ acceptance\ rate\ (\%)$$

The share of EVBs fitting the packaging is based on a scaling market share, starting in 2023 by using an estimate from the data presented in *Appendix C: Battery Models* with a finishing value in 2030 based on the market share estimate from *Appendix B: Most Sold EVs* for 2030. Shares of EVBs fitting the packaging for years between 2023 and 2030 are linearly scaled, using the same logic presented as the combined case in *5.1.3 Estimated Future Flows*.

Based on the number of batteries captured, it is possible to estimate the amount of packaging units needed to support this operation. The number of packages needed is affected by two factors, the average time a package spends in storage and whether EVBs are packed together in a package. The average time in storage affects how many packages are bound up in storage and unavailable for collecting additional batteries. At the same time, the number of packages needed can be reduced if it is possible to pack several EVBs in one package. This is determined by the dimensions of the batteries and the package and is an assumption that is built into the model.

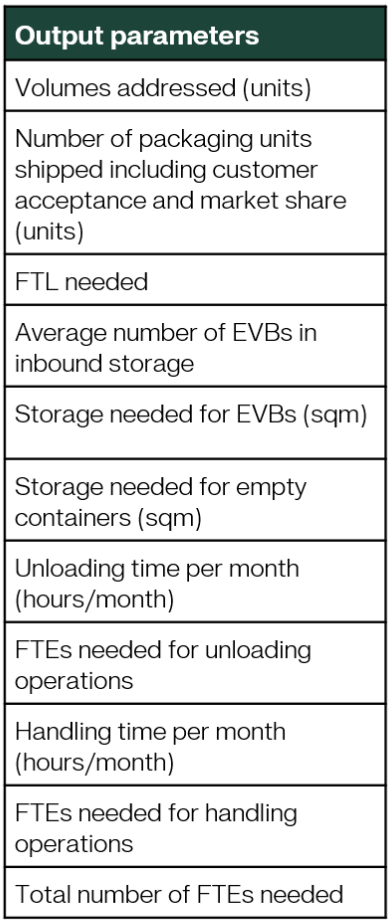
Following the captured volume estimates, the needed number of FTLs (Full Truckload) can be calculated. It is derived from an efficiency calculation where, given the dimensions of a packaging design, the number of packages fitting in a truck is measured. The efficiency is calculated by adding a material thickness of 23 millimeters and a bottom height of 144 millimeters (same height as an EUR-pallet) to the inner dimensions of the packaging. The packaging units are then arranged to fit as many units as possible in the truck. The measurements used for the truck size is the same as the European standard for an FTL which is 13 600 x 2 450 x 2 450 millimeters. When the number of packages in a truck is known, the number of FTLs needed can be calculated in two ways. The first is by assuming a maximized fill rate and hence dividing the number of battery units captured by the packaging design with the number of packages per truck if they are arranged to fit as many as possible. The second way is to assume a certain fill rate, for example 80%, which decreases the number of units transported per truck, thus requiring more FTLs.

Next follows the parameters related to warehousing needs. The first one is the average number of EVBs stored in the warehouse, which will also indicate the need for storage space. The average number of EVBs in storage is estimated by multiplying the captured volume with the average amount of days in storage, given by the case company, and then dividing that figure with 365 to get the average amount of days that an EVB spends in storage. This number is then used to estimate the need for storage space, both when packages are stacked and when they are not. The need for storage space is then calculated as the average amount of packages in storage, divided by the number of packaging units that can be stacked on top of each other, times the bottom area per package, see *equation (5.3)*. The same calculations are done for empty packages where they are estimated to be foldable. These figures can then be adjusted to consider stackability, by dividing the storage needed with the number of packages stacked on each other, as well as adding a certain warehouse fill rate requirement.

$$\text{Needed storage space} = \left(\frac{\text{Captured volume}}{\text{Full units stacked}} + \frac{\text{Captured volumes}}{\text{Empty units stacked}}\right) \cdot \text{Bottom area of one unit} \tag{5.3}$$

Continuing, the FTE need is estimated. Observing the operations at the case company, the warehousing process is mainly connected to unloading and handling activities. These activities are assumed to be executed by the same staffing pool. Looking at the unloading activities, the first parameter estimated is the unloading time per month. It is calculated from multiplying the number of packages handled per month with the average unloading time for one FTE for one FTL. This figure is given by the case company and is in this model fixed to 4 hours to facilitate the calculations. In reality the unloading time could vary, for example depending on the fill rate of a truck and the FTEs' experience level. The number of FTEs needed for unloading is then calculated as the total unloading time divided by 160 hours, which is the assumed average work time during a month. The second parameter related to the number of FTEs is the handling operations and the time it takes. With the same logic as described above, the number of FTEs needed for handling operations is calculated by assuming an average handling time of 30 minutes per package. This covers actions such as moving the EVBs to discharging or relocating them in the warehouse. Finally, the absolute number of FTEs needed is calculated by summarizing time needed in unloading and handling operations, rounding it upwards to get the total amount of FTEs that a battery recycler has to employ for its internal operations.

Table 5.3: Operational output parameters that are generated from the model.



Output parameters
Volumes addressed (units)
Number of packaging units shipped including customer acceptance and market share (units)
FTL needed
Average number of EVBs in inbound storage
Storage needed for EVBs (sqm)
Storage needed for empty containers (sqm)
Unloading time per month (hours/month)
FTEs needed for unloading operations
Handling time per month (hours/month)
FTEs needed for handling operations
Total number of FTEs needed

5.2 Creating Design Alternatives

As part of evaluating whether a battery recycler would benefit from a unified packaging and logistics solution, a main step for this study is to analyze the relation between the packaging design and its operational performance as discussed in *2.3 Packaging Theory*. Therefore, this chapter of the report is divided into two parts, where the first one presents five packaging design alternatives and the second investigates the operational performance of each design, using the operational model presented in *5.1.4 Operational Model*.

5.2.1 Design Alternative Choice

With its large impact on the commercial and operational effects, one of the key decisions to take when designing the packaging solution is its inner dimensions. Since the dimensions of the packaging limit what batteries can be packed, they can be used to derive a share of the EVB recycling market that is addressable with a given design. Therefore, by using the inner dimensions of a design alternative, it is possible to estimate the potential market capture that a design has.

To see the gradual increment of the addressable market when increasing the packaging dimensions, five design scenarios with varying length, width and height are used. All design alternatives were modeled after the flat battery pack archetype. The five design alternatives are presented in *table 5.4*, where Alternative 1 is the smallest and Alternative 5 is the largest. The dimensions for the alternatives are designed so the smallest design, Alternative 1, addresses approximately 25% of the market and the largest, Alternative 5, addresses close to 100%. The other alternatives are incrementally increasing in size and market share. Note that when using this logic, the larger a package is, the larger the market it can address. However, by using a too large design the recycler risks higher operations costs, and a suboptimal solution which will be further discussed.

Table 5.4: The dimensions for the five packaging design alternatives with varying length, width and height

Design Alternative	Length	Width	Height	Market Share
Alternative 1	1500	1200	300	26%
Alternative 2	1725	1350	350	44%
Alternative 3	1950	1500	400	60%
Alternative 4	2175	1650	450	91%
Alternative 5	2400	1800	500	98%

5.2.2 Operational Performance

This section presents the operational performance for each of the five packaging design alternatives using the model from chapter *5.1.4 Operational Model*. The results are presented in *table 5.5*, including the addressed volume in EVB units for each alternative, and the operational performance for the period 2023 - 2030. The shares presented for the addressable market are based on the differing market share estimates presented in *5.1.4 Operational Model*.

Table 5.5: Overview of operational performance for each design alternative. The market addressed (%) is the range between the addressed market based on Appendix B and the addressed market based on Appendix C: Battery Models. For FTLs needed, Average EVBs in storage, Storage needed, and FTEs needed, the range represents the operational output for 2023 and 2030.

	A1	A2	A3	A4	A5
Market addressed (%)	**26% - 43%**	**44% - 57%**	**60% - 70%**	**81% - 91%**	**94% - 98%**
Volumes captured					
2023	9 600	12 500	15 400	17 800	20 700
2024	9 600	12 800	16 000	19 200	22 100
2025	12 700	17 500	22 200	27 700	31 400
2026	18 700	26 600	34 200	44 300	49 800
2027	28 100	41 300	53 900	72 600	80 600
2028	43 300	66 200	87 900	123 000	135 100
2029	53 200	85 100	115 000	167 200	181 600
2030	64 900	109 100	150 300	226 900	244 100
FTLs needed	190 – 1 300	350 – 3 000	640 – 6 261	740 – 9 500	990 – 11 620
Average EVBs in storage	52 – 360	70 – 600	50 – 820	100 – 1 240	110 – 1 340
Storage needed (sqm)	64 - 440	100 – 850	140 – 1 300	180 – 2 340	240 – 2 890
FTEs needed	4 - 21	5 - 37	6 - 57	7 - 86	9 - 96

As seen in *table 5.5*, design Alternative 1 which is the smallest packaging, addresses the smallest volume each year. This means it will most likely generate less revenue than a larger solution, but at the same time it also requires less storage space, FTEs, and FTLs which indicates that it would not cost as much to operate. On the other hand, Alternative 5 addresses almost the entire market but requires more extensive internal operations due to the larger volumes captured. This tradeoff between lower costs from smaller operations against the risk of lower revenue from less batteries is of interest for the battery recycler and needs to be further analyzed by adding cost and revenue to the operational elements.

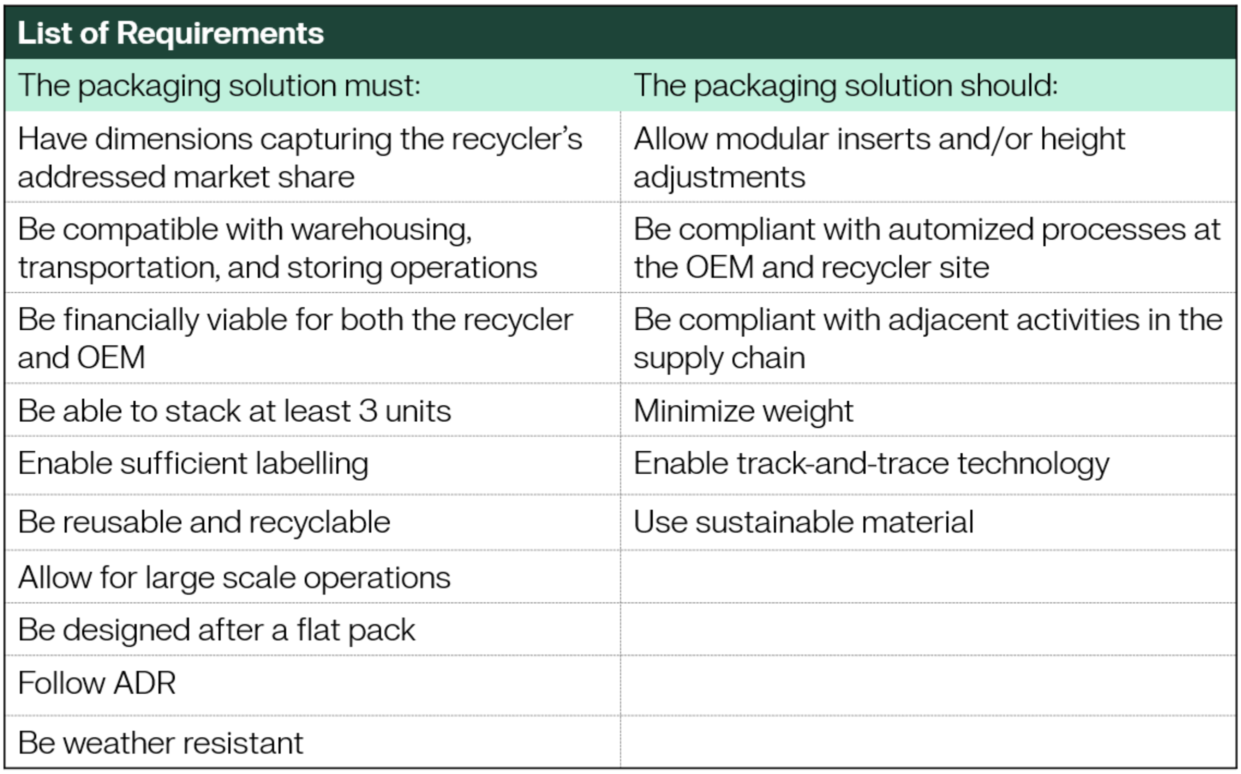
5.3 Summary

A key finding in the chapter is that the flat archetype emerges as a dominant design when categorizing the product sample in *Appendix C: Battery Models*. Hence, the archetype seems to be a suitable prototype for the packaging design when aiming to fit as many batteries as possible. This design choice also appears to be future proof when investigating what EVBs will be recycled in 2030, indicated by the batteries in the most sold car models during 2019-2022 which will be recycled in the coming 5-15 years. The decision to use the flat archetype for the packaging design is therefore supported by the fact that it is the largest archetype, fitting most of the other archetypes, as well as it is the most common design, by both market estimates.

By using the flat pack dimensions as a base for the design alternatives, and the operational model, it is concluded that a larger packaging design addresses a larger market, comparing 94-98% for Alternative 5 to 26-43% for Alternative 1. At the same time, the larger volumes captured lead to more extensive operations, seen in *table 5.5*, which will result in larger costs. The next step is therefore to find a preferred packaging design by adding costs to the operational elements to balance the tradeoff between a potential revenue increase from larger volumes captured and higher costs from extensive operations.

By summarizing chapter 5, research objectives 1 and 2 can be answered by a list of requirements for future solution designs. The list is based on everything written until this point and divided into one column with hard requirements (left) and one column accounting for optional requirements that can improve performance of the solution. The list is presented in *table 5.6.*

Table 5.6: List of requirements for future packaging solutions.



List of Requirements

The packaging solution must:	The packaging solution should:
Have dimensions capturing the recycler’s addressed market share	Allow modular inserts and/or height adjustments
Be compatible with warehousing, transportation, and storing operations	Be compliant with automized processes at the OEM and recycler site
Be financially viable for both the recycler and OEM	Be compliant with adjacent activities in the supply chain
Be able to stack at least 3 units	Minimize weight
Enable sufficient labelling	Enable track-and-trace technology
Be reusable and recyclable	Use sustainable material
Allow for large scale operations	
Be designed after a flat pack	
Follow ADR	
Be weather resistant	

Based on these findings, the report continues in the next chapter with evaluating the packaging design alternatives, both from a financial and a strategic perspective. Finally, when the findings from the evaluation chapter are combined with the findings from the analysis, it is possible to answer the research question and the last research objective in chapter *7. Conclusion*.

6. Evaluation

Based on their operational performance, the design alternatives presented in the previous chapter are now evaluated and compared to each other based on their financial performance. Other factors, seen as complementary strategic decisions, are also presented, evaluated, and connected to different strategic reasonings. These qualitative aspects are then combined with the design alternatives and together they are evaluated from a strategic point of view and connected to different supply chain strategies. By following this evaluation, an EVB recycler should be able to choose the packaging solution best fitted for their operations. A high-level summary of this section, its structure as well as the key findings, can be seen in Figure 6.1.

6.1 Cost Evaluation

Key insights

- The larger design alternatives have a larger total potential cost saving due to its larger market shares
- The more niched design alternatives can optimize the operation more, thereby generating a larger relative saving compared to their base case
- Using joint packing significantly improves the savings

6.2 Sensitivity Analysis

Key insights

- The business case for each alternative is relatively robust, requiring drastic changes to become unprofitable
- The larger alternatives are more sensitive for change due to their lower relative savings
- Material cost, company market share, and storage time are all linearly affecting the total savings
- Addressed market share change depending on the dimensions of the packaging solution. Here, it is important that the case company find the thresholds where the market share is more affected by change and designs their dimensions accordingly

6.3 Qualitative Evaluation

Key insights

- The qualitative aspects of a packaging design can be used to tweak the solution to better fit the recycler's business and supply chain strategy
- The most prominent decisions are connected to material use, sustainability aspects, operational efficiency, flexibility and modularity, and lock-in effects.

6.4 Strategic Evaluation

Key insights

- Each design alternative have different impact on the supply chain performance, thereby affecting the strategic placement of the recycler's operation
- By selecting the right dimensions for a packaging solution, a recycler can target their sought after market
- The smaller alternatives have competitive advantages in being more niched, offering a more complex solution to the customers
- The larger alternatives have competitive advantages in addressing larger markets, competing with price and an efficient supply chain setup

Figure 6.1. A summary of the key insights from each section in the evaluation chapter (source: own illustration)

6.1 Cost Evaluation

To be able to answer whether a battery recycler would benefit from offering a unified packaging solution, an important part to evaluate is if the solution is financially beneficial. The financial part of the evaluation can broadly be divided into costs and potential revenue. However, according to the case company it is difficult to get a quantitative estimate of the OEM's willingness to pay for this type of service. Therefore, the quantitative evaluation will mainly focus on the cost parameters, evaluating potential revenue and the OEMs willingness to pay as a qualitative aspect instead of including it in the quantitative evaluation. The quantitative part of the financial evaluation focuses on a cost comparison between the packaging design alternatives and a baseline case. The baseline case matches the case company's current operations, and each design alternative is compared to this baseline using the addressed volume for that specific alternative. With this analysis, the comparison highlights potential cost savings from a new solution, which is reflected by the difference in cost and operational performance.

Given this setup, the chapter evaluating costs is divided into two parts, where the first one explains the model and describes its logic, whereas the second part evaluates and compares the financial performance between the five packaging design alternatives and the baseline case.

6.1.1 Cost Comparison Model

The model that is used to financially evaluate packaging designs is connected to the model presented in *5.1.4 Operational Model* but is expanded by adding costs to each operational element. By providing the packaging dimensions as input the financial model calculates the total costs, using the operational model as an intermediary step to determine the operational elements.

The costs have been divided into capital expenditures (capex), consisting of potential machinery investment, and operational expenditures (opex) consisting of costs for material, FTEs (Full Time Equivalent), warehouse rent and transportation. The capex costs have been identified together with the case company and are the investments needed to support the operations. Given the case company's situation, a small general investment is used to simulate the startup investments connected to the new packaging solution. To calculate the yearly capex costs, the total investments have been divided by the eight years between 2023-2030. Opex, on the other hand, requires a more exhaustive explanation on how they are calculated.

First, the yearly amount of packaging needed is calculated by multiplying the captured volume with the yearly turnover that is assumed to be the average cycle time divided by 365 days of operations, see *Equation (6.1)*. The average cycle time is an estimate from the case company based on the average storage time for EVBs and the average storage time for empty packaging units. The yearly packaging need can then be used to estimate the yearly purchased volume. This is done by subtracting the remaining packaging units from previous years from the total need, see *Equation (6.2)*. The remaining packaging units from previous years are dependent on the packaging unit lifetime, given as an estimate from the case company. Further, using the purchased volume, the yearly material cost is calculated by multiplying the purchased volume with the purchasing cost per unit, see *Equation (6.3)*.

$$(6.1)\ Yearly\ packaging\ need = captured\ volume \cdot \frac{Average\ cycle\ time}{365}$$

$$(6.2)\ Purchased\ volume = yearly\ need - viable\ units\ from\ previous\ years$$

$$(6.3)\ Material\ cost = Purchasing\ cost \cdot Purchased\ volume$$

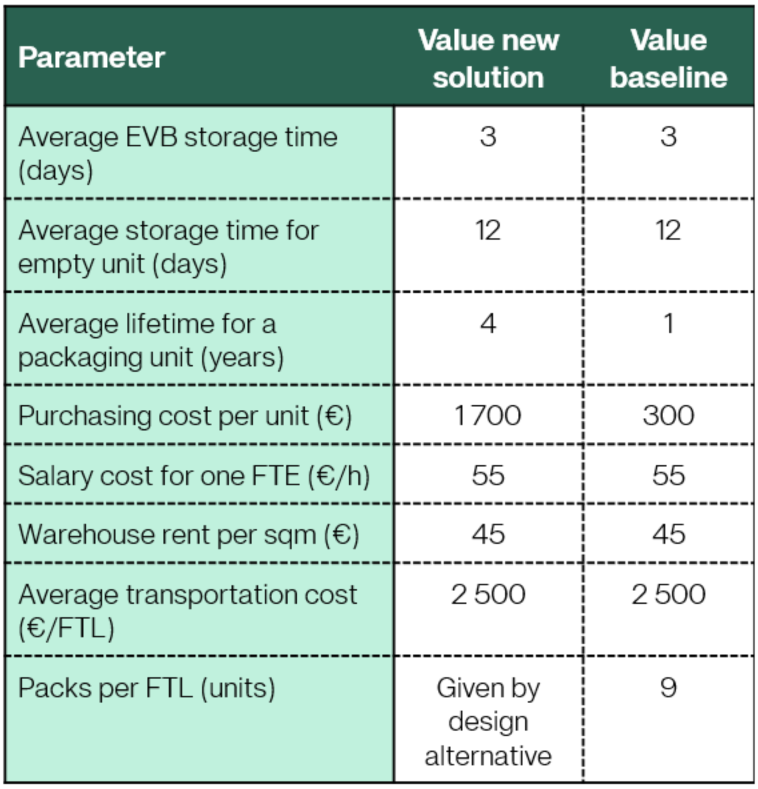
As for the FTE cost, it is a product of the number of FTEs needed multiplied with their yearly salary cost, see *Equation (6.4)*. Further, the warehouse rent is the product of the cost per square meter storage times the needed area for storing packages, see *Equation (6.5)*. Lastly, the transportation cost is calculated as the cost per FTL times the amount of transport in a year, see *Equation (6.6)*. The amount of transport in a year is based on the number of packages transported in a year and the number of packages that fit in a FTL. With support from this model, the cost evaluation can be continued by applying the model to the design alternatives. An illustrative example of parameters used as input based on the case company's operational situation are presented in *table 6.1*. These parameters are used both when calculating the cost of the new solution and the baseline case.

$$(6.4)\ Yearly\ FTE\ cost = Number\ of\ FTEs \cdot Yearly\ salary\ cost\ per\ FTE$$

$$(6.5)\ Warehouse\ rent = Cost\ per\ sqm \cdot Needed\ storage\ space$$

$$(6.6)\ Transportation\ cost = Number\ of\ FTL\ per\ year \cdot Cost\ for\ one\ FTL$$

Table 6.1: Illustrative example of cost parameters used for calculations, given by the case company. Note: These numbers are illustrative and not from the company's operation.



Parameter	Value new solution	Value baseline
Average EVB storage time (days)	3	3
Average storage time for empty unit (days)	12	12
Average lifetime for a packaging unit (years)	4	1
Purchasing cost per unit (€)	1 700	300
Salary cost for one FTE (€/h)	55	55
Warehouse rent per sqm (€)	45	45
Average transportation cost (€/FTL)	2 500	2 500
Packs per FTL (units)	Given by design alternative	9

6.1.2 Cost Comparison

As stated, the cost comparison is made between the baseline case and each of the five design alternatives. The baseline case is defined by current abilities at the case company, and to make a fair comparison the packaging dimensions, and hence the battery volume addressed, are set equal for the baseline case and the design alternative it is compared to. Meaning, that the baseline case will differ in volume in accordance with the design alternative it is compared to. However, what differs between the design alternatives and the baseline is that in the baseline case, the amount of EVBs packed in a truck is limited to eight battery packs, according to estimates from the case company. This capacity limitation will have operational effects, increasing the number of FTLs needed, which in turn will lead to cost differences when the two setups are compared, capturing the same volumes. To mimic the current situation, what also differs is that the baseline case is assumed to be a simple construction costing 120 euros per package that has a lifetime of one year.

The cost comparison between each packaging design alternative and its corresponding baseline case is shown in *Figure 6.2*. It presents the total potential cost savings in euros for each year, calculated using the cost comparison model.

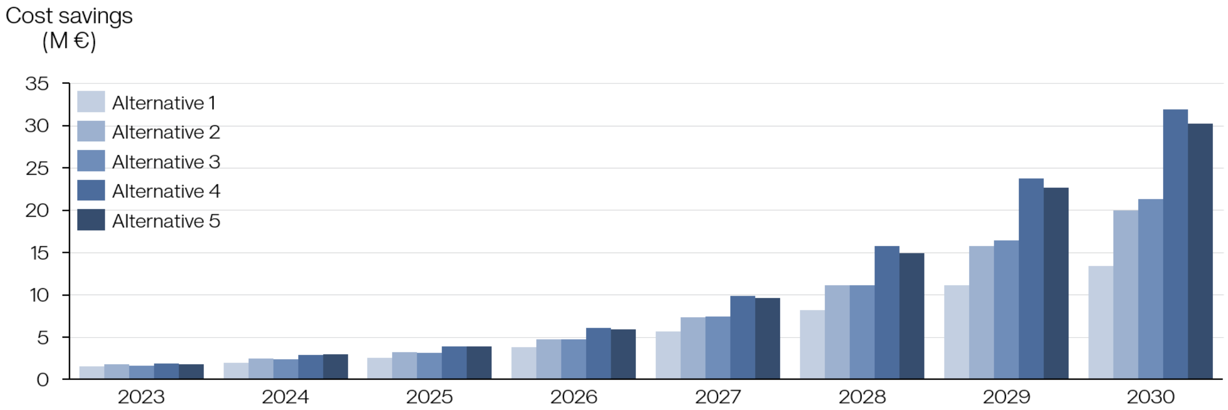


Figure 6.2: Overview of the cost comparison between each packaging design alternative and its corresponding base case. The table shows the total potential cost savings for each year and each comparison.

Looking at the cost savings in *Figure 6.2*, all alternatives generate cost savings from the start. Alternative 1 results in the smallest savings, whereas Alternative 4 generates the largest savings, except from 2024 where Alternative 5 saves the most. The size of the cost savings seems to follow the increasing market share and the inner dimensions of the packaging units. This is logical since it is the absolute savings, not a percentual share. The larger market share for larger packaging units generally leads to a larger captured volume, and hence a larger impact when comparing euros saved. There are however some interesting learnings from the graph, first being the just mentioned relation between collected volumes and absolute saving.

Second, by comparing the cost savings in *table 6.2* with the market share from *table 5.4*, they do not scale linearly. If they had, Alternative 4 would for example generate more than 3 times larger cost saving than Alternative 1 since they address 91% and 26% of the market, respectively. However, this is not the case. It is also clear that the alternatives differ in their percentage of cost cutting compared to their baseline case. Here, Alternative 1 reduces costs by approximately 65% over the seven-year period, while the larger Alternative 5 reduces 40% of the total costs. This is illustrated in *table 6.2*. The reason behind this could be that the smaller market share of Alternative 1 is a selected sample, which results in a more uniform sourcing situation. By addressing only smaller EVBs, the packaging design can control the variability in the sourcing situation, and hence reduce the uncertainty connected to the battery dimensions. What is happening is that the recycler chooses a subpart of the market, based on the EVB dimensions, and therefore only has to consider the more niched needs of that particular part. By doing this, the variability is reduced. Reducing product variability is a key aspect in standardizing packaging solutions, in accordance with *2.2 Supply Chain Theory* as well as *2.3 Packaging Theory*. Reduced variability is also one of the main reasons why process innovation only succeeds when a design standard or dominant design is set. Without it, the efficiency improvement of a standardized solution would be too low due to the varying product needs. By the establishment of a dominant design, it is logical that selecting a subcategorization of the market with more homogeneous needs and dimensions, as done with Alternative 1, will be more cost efficient. In contrast, if the market share was not a part of a selected sample, and instead the same share but randomly assigned from the entire EVB market, the result would likely be much worse from a cost saving perspective.

Table 6.2: The percentual cost saving for each alternative and year, compared to their respective baseline case.

	2023	2024	2025	2026	2027	2028	2029	2030
Alternative 1	53%	69%	66%	67%	67%	63%	69%	68%
Alternative 2	47%	63%	61%	59%	59%	55%	61%	61%
Alternative 3	35%	49%	46%	46%	45%	42%	47%	47%
Alternative 4	35%	50%	46%	45%	45%	42%	47%	46%
Alternative 5	28%	44%	40%	39%	39%	36%	41%	41%

Another reason for the differing cost savings compared to the baseline case, presented in *table 6.2*, is likely the transportation cost. Transportation is a major contributor to costs, looking at the cost comparison model. Therefore, a design alternative that can reduce transportation costs will perform much better than an alternative that has the same percentual cut on another cost bearer. Alternative 1 uses the smallest packaging design and can hence fit the most number of EVBs in one FTL, therefore reducing transportation cost the most. Another sign of importance for the transportation cost can be observed when looking at the percentual cost savings for Alternative 3 and 4. They both allow 24 EVBs to be packed in one FTL, given that the total weight does not exceed the allowed weight for the vehicle. Given this similarity, the almost equal cost savings percentages strongly indicate that transportation costs have a significant effect on the cost savings.

Based on these observations, different design alternatives are relevant depending on the strategic direction of the recycling company. If the battery recycler has the resources and is confident, they will capture the market share used in this cost comparison, Alternative 4 will be of most interest. By implementing this, the recycler can save the largest total amount, and have a flexible packaging solution that can address the entire market. The drawbacks of this alternative are the larger investment cost and the fragility in the estimated market. Alternative 4 has a smaller percentage cost saving and is therefore more sensitive to changes in the case assumptions. This can be problematic given that the alternative relies on a relatively large market capture, an estimate that is prone to change. On the other hand, if a recycler lacks resources for a packaging solution, and a smaller market share with smaller EVBs is in line with their strategy, Alternative 1 is most attractive. Here, the total savings are smaller, but the relative cost saving to the baseline case is close to 70%.

6.1.3 Cost Comparison Using Joint Packing

A parameter that could potentially change the cost evaluation above is the number of EVB units carried by each packaging alternative. Until now, the thesis has assumed only one EVB in each packaging unit. However, when evaluating the battery and packaging dimension, it became clear that some packaging designs fit more than one EVB, and therefore operate more efficiently. Using joint packaging is an efficient way of improving the fill rate in each packaging unit, and thereby also in transportation and warehousing situations, as stated in *2.3 Packaging Theory*. This chapter adds an option to the cost comparison model where more than one EVB can be packed in the evaluated alternative and investigates how this option affects the cost comparison.

Starting with the operational side of this option, EVBs are now assumed to use a joint package if more than one of the same EVB model can fit into the design alternative evaluated. This means that the model never assumes a mix of EVBs in the same packaging unit, which corresponds to a more restrictive assumption where OEMs only pack one EVB type at a time. If OEMs in practice can further optimize the fill rate in the packaging unit, it will only improve the output of this estimate. In addition, the model also considers if more than two EVBs can be packed in the packaging unit, which further improves the efficiency of the solution.

For the total cost savings, a similar pattern as in *6.1.2 Cost Comparison* can be observed, where the total savings increase with time, and generally with the size of the packaging solution. What differs, however, is the amount saved where the average cost saving has increased 42% and the largest amount saved differs with over 9 million euros. This improvement is a direct consequence of the joint packing solution, and how it handles the same volumes with a reduced cost of transportation, material, handling, and storage time. Another interesting finding is that Alternative 5 has a higher potential saving than Alternative 4, which was the alternative with the largest savings when each pack only carried one EVB. This is likely due to the fact that Alternative 5 has larger inner dimensions and therefore the ability to pack more batteries using the joint packaging approach. This can be seen in *Figure 6.3*.

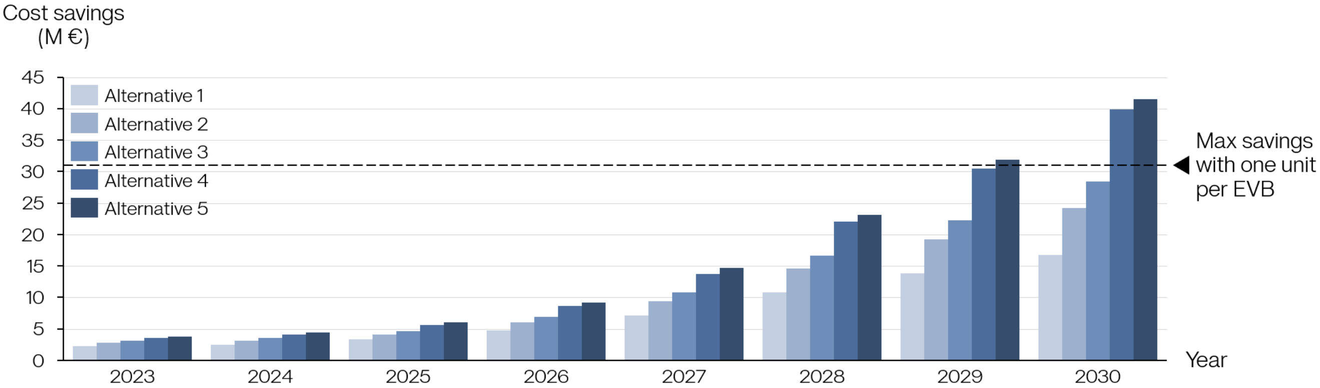
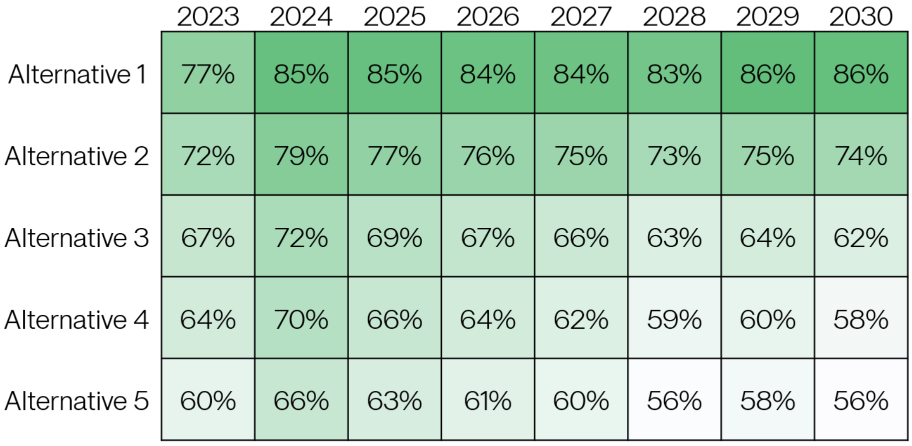


Figure 6.3: Overview of the cost comparison between each packaging design alternative and its corresponding base case. The table shows the total potential cost savings for each year and each comparison, given the joint packing strategy.

Further, the joint packaging approach also affected the percentual cost savings, compared to the baseline case. Comparing the previously presented *table 6.2* with the updated *table 6.2*, the percentages have increased with the same 42% as shown in *Figure 6.3*. The reason is the same, just illustrated using percentages instead. What has changed, however, is the distribution of savings over the years. Previously, the savings increased with time, but in *table 6.3*, another trend can be seen. For the smaller alternatives, the savings are relatively stable and comparable to the previous case. However, with time the relative savings decrease in size for the larger alternatives, 3 to 5. This is reversed from the trend only using one EVB per packaging unit. The trend indicates that joint packing is more beneficial in the early years of operations, however, the relative difference between the savings is too small to lay base for any larger operational insights.

Table 6.3: The percentual cost saving for each alternative and year, compared to their respective baseline case.



	2023	2024	2025	2026	2027	2028	2029	2030
Alternative 1	77%	85%	85%	84%	84%	83%	86%	86%
Alternative 2	72%	79%	77%	76%	75%	73%	75%	74%
Alternative 3	67%	72%	69%	67%	66%	63%	64%	62%
Alternative 4	64%	70%	66%	64%	62%	59%	60%	58%
Alternative 5	60%	66%	63%	61%	60%	56%	58%	56%

In addition, the difference between the smallest and largest cost saving is lower when using joint packaging. The approach improves efficiency in the larger solutions, hence reducing the percentual cost saving difference between the design alternatives. By doing this, more weight can be put on the strategic and qualitative aspects of the evaluation.

Given the cost comparison, a further evaluation of the qualitative and strategic aspects is needed, as well as a sensitivity analysis for the major parameters in the cost comparison model. These comparisons are presented in the chapters below.

6.2 Sensitivity Analysis

The cost evaluation in the previous chapter is based on a model predicting the future market development, and thereby associated with uncertainty. For this reason, it is useful to perform a sensitivity analysis, evaluating assumptions and input parameters used in the model. By tweaking these parameters both the robustness of the model and the margin for the design alternatives will be tested. In the case where a certain parameter is found to be sensitive, it will require more attention from the recycler who has to decide how to relate to that particular risk. The sensitivity analysis is divided into four parts where the material cost, the market share, the operational efficiency, and the packaging dimensions are investigated one at a time.

6.2.1 Material Cost

The first parameter to be analyzed is the material cost. The material cost is a significant cost contributor, standing for around 15% of the total costs depending on which design alternative and year being analyzed. However, the cost of material could change for several reasons, for example if the market price for a material fluctuates, if the packaging design requires a new specific type of material, or if the cost per package is lowered due a changed purchasing situation. The sensitivity analysis for material cost is here fixed on the year 2023, where the impact of a material price increase is modeled against the relative cost savings in percentage for each alternative. In the original model, the material price for the packaging alternatives was set to 1 500 euros, which is the starting point for the analysis and the leftmost value in *Figure 6.4*.

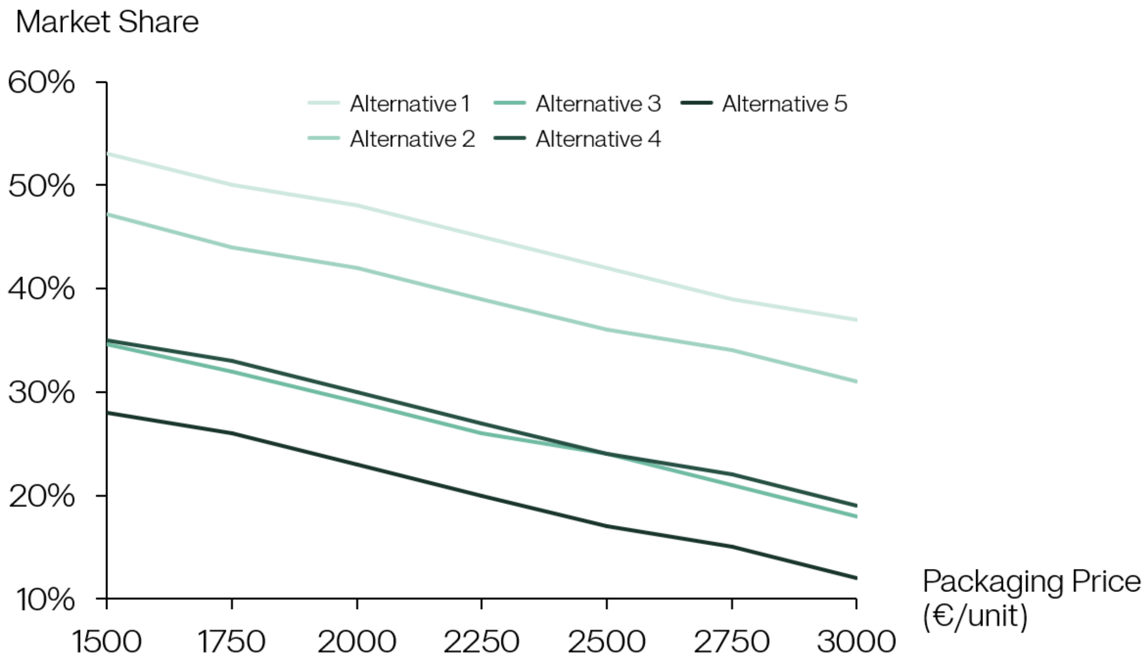


Figure 6.4: Plots the packaging price against the cost savings in percentage for each of the five packaging design alternatives.

In Figure *6.4*, it can be seen that a duplication of the material cost, from 1 500 euros to 3 000 euros, causes an almost 20 percentage points decrease in the savings for all alternatives. The decrease in savings is significant but it should however be noted that the price in the original model is already set quite high according to information received from suppliers by the case company, which is why a price duplication seems extreme. Although, it is good to be on the safe side with regards to the recent years' instability in material prices. Seen in the graph is that the packaging price has a linear impact on the percentual cost savings and affects all alternatives with an equal decrease in percentage points. However, since the savings for the design alternatives start from different levels, a material price increase has more severe consequences for Alternative 5 than for Alternative 1, converging towards levels closer to zero savings. Lastly, the graph shows the importance of negotiating a good price from the supplier, independent of the design alternative.

6.2.2 Market Share

One parameter that cannot be directly controlled by the battery recycler is its market share, meaning that it is challenging to accurately estimate the captured EVB volumes. The market share will impact the captured volumes and accordingly lays the foundation for the case. The market share can be influenced by competition from direct competitors that recycle batteries, but also from actors with an interest in collecting EVBs for other purposes, for example second life applications. Thus, given the still early phase of

European battery recycling it is useful to analyze the impact if the market share is lowered from the 30% that was assumed in the original model. *Figure 6.5* shows the savings in euros when comparing the design alternative to the baseline case. Note that for the analysis, the time is fixed for the year 2024.

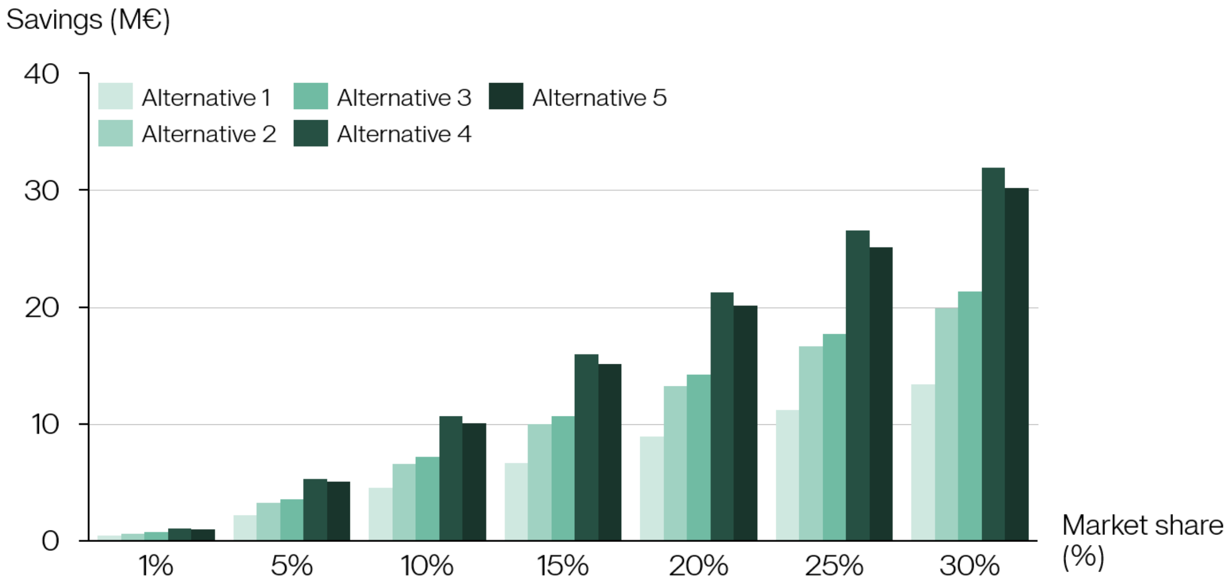


Figure 6.5: Plots the savings in euros against the market share for each of the five packaging design alternatives.

The model is built so that the market share parameter affects the design alternative and its baseline case equally. It is therefore more interesting to show the savings in euros rather than percentage, since a 50% decrease in market share leads to an approximately 50% decrease in savings. Thus, this analysis provides more insights if an absolute threshold value is set for the savings level, since the savings in percentage remains the same. For example, if the recycler requires cost savings of more than 1 000 000 euros, a market share of around 15% is required for all alternatives, where Alternatives 4 and 5 allow slightly lower shares since they capture larger volumes. Therefore, before making any investment decision in a packaging and logistics solution, it is important for the recycler to investigate what market share that is needed to meet the expected cost savings and reflect about whether that share is feasible in reality.

6.2.3 Operational Efficiency

The operational efficiency is affected by the time it takes for an FTE to unload and handle a package as well as the time a package spends in storage. Both the unloading and handling times were set to conservative levels in the original model, 4 hours respectively 30 minutes but would both affect the business case negatively if they turn out to be longer. If any of the times are longer, it would require more working hours to handle the same battery volumes resulting in higher salary costs. The same logic applies for the time spent in the warehouse for both filled and empty packages. If these times turn out to be longer than estimated in the model, 2 days and 10 days, it will require buying more packages to handle the same battery volumes. Conducting the sensitivity analysis, the case company is more confident in the estimation of handling times than the storage times. This leads the analysis to focus on investigating the financial impact from a changed storage time. The results are shown in *Figure 6.6*, where the numbers are taken from a fixation in the year 2023.

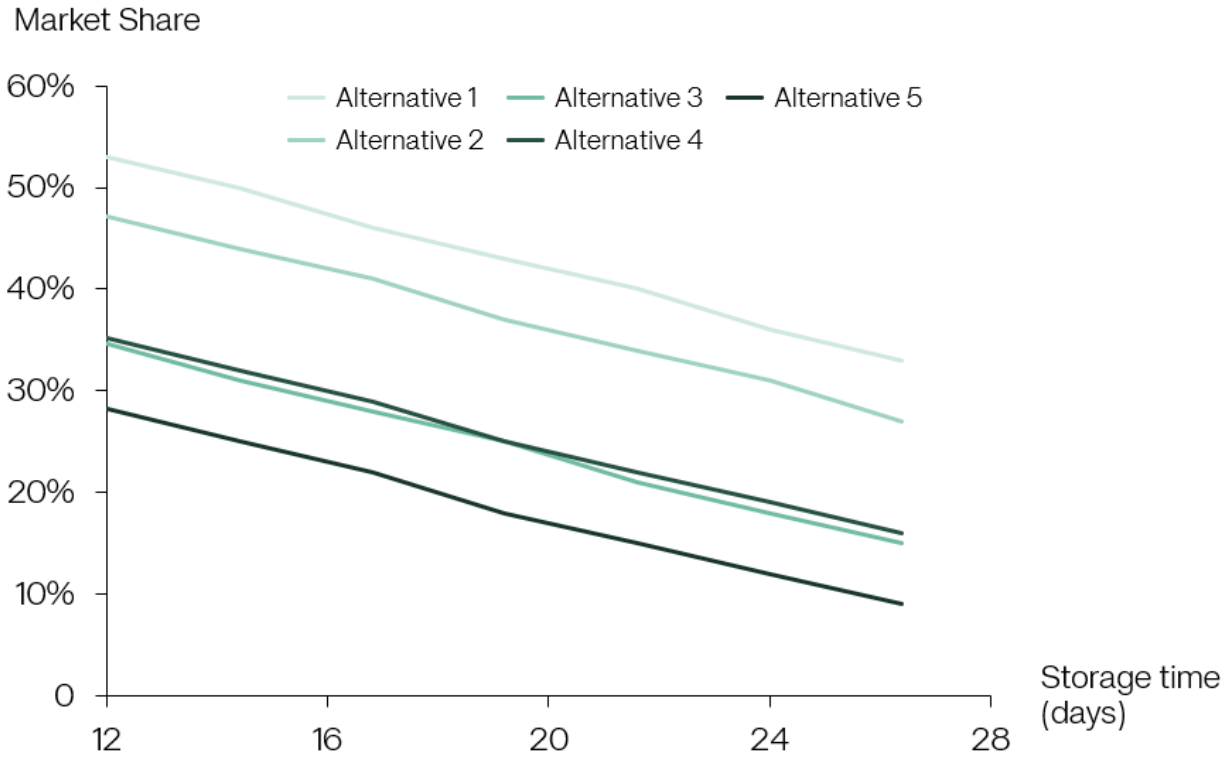


Figure 6.6: Plots the savings in percentage against the percentage increase in storage time for each of the five packaging design alternatives.

Figure 6.6 shows a linear relation between an increase in storage time and the percentual cost savings. It can be seen that a duplication of the time a package spends in storage results in a cost savings decrease of approximately 15 percentage points for all design alternatives. With an initial value of 12 days in storage, it is not far-fetched that such an increase can happen, especially in the early phases of operations where standards are yet to be set and startup problems occur. Therefore, it is important that the case company monitors their storage time and ensures that their system is appropriately managed. Further, comparing the design alternatives, it can with a similar logic as the one used for material cost be seen that an increase in storage times has more severe consequences for Alternative 5 than Alternative 1, since its percentual cost savings starts from a lower level.

6.2.4 Addressable Market and Packaging Dimensions

As a fourth and final part of the sensitivity analysis, the impact of packaging dimensions on the addressable market is investigated. For this analysis, 9 packaging dimension alternatives are created, where the width and height are fixed, and the length is varied along the X-axis. The dimensions are then used to calculate the addressed market share from *Appendix B: Most Sold EVs*, reflected by the Y-axis. The analysis aims to identify threshold values, from where a small change in the dimensions leads to a significant increase in the addressable market. At the same time, it is also possible to see the dimension changes that have smaller impact on the addressable market and rather contribute with a worsen space utilization due to its larger size. The results are shown in *Figure 6.7*. In the graph, dimensions with the same height have the same color (250, 350 or 500 millimeters), and the different width alternatives (1 250, 1 500 or 1 750 millimeters) are symbolized with a dotted, dashed, or solid line.

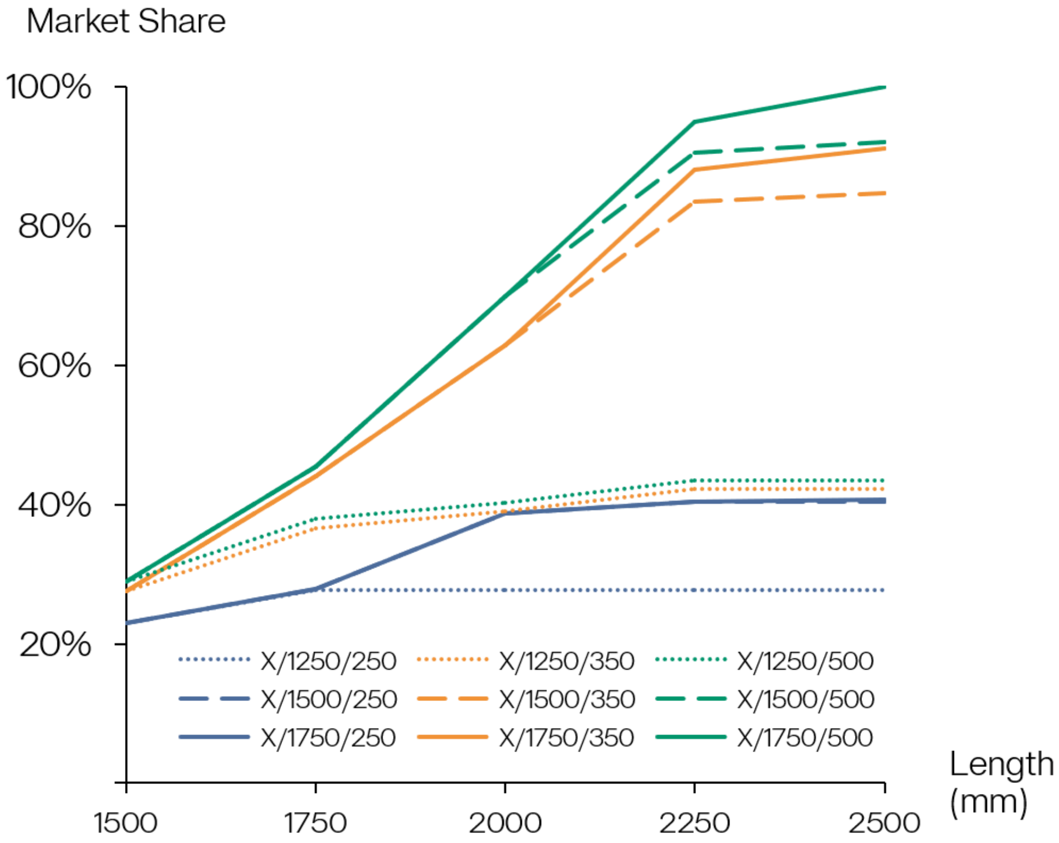


Figure 6.7: Shows the addressable market for different dimensions where the width and height are fixed, and the length is altered.

First, as moving to the right in the graph, it becomes obvious that a longer package addresses a larger market, but that the height and width serve as limitations for how much the recycler would benefit from a length increase. Analyzing the smallest alternatives where the width is limited to 1 250 millimeters (dotted lines) there is a jump in the addressable market from 28% to 42% when the height is increased from 250 to 350 millimeters (comparing blue and orange lines). However, the increase when adding an additional 150 millimeters, comparing the orange and green line, the larger package with a height of 500 millimeters addresses 44% of the market, which is only a marginal increase. This is an example of where a larger package does not result in a significant increase in market share, and instead risks increasing the operational cost and worsening the fill rates by its larger dimensions.

Moving on to the packages with a width of 1 500 millimeters (dashed lines), there is a significant jump in addressable market from the alternative with 250 millimeter height (overlapped by the solid blue line) and the 350 and 500 millimeter packages. The 250 millimeter reaches a maximum of 40% whereas the larger sizes reach 85% and 92% for the higher designs. For this width, there is also a bigger difference between the two larger heights, where the 500 millimeter design covers 8 percentage points more than the 350 millimeter design. The three designs with 1 750 millimeter width follow the same pattern where the smallest option results in a significantly smaller market share, and the largest option has a slightly larger share than the middle option. However, if the package is intended to address the largest market share possible, the 500 millimeter option is preferred over the 350 millimeter option. This since the dashed green line (X/1500/500) addresses a higher share of the market than the solid orange line (X/1750/350), regardless of its smaller width.

From this analysis, several threshold values emerge. For example, there is a large gap in market share between the X/1250/350 option and the X/1500/350 option indicating that the 250 millimeter width increase from 1 250 to 1 500 millimeters is particularly profitable when wanting to address a larger market share. In the same way, the height increases from X/1250/350 to X/1250/500 results in only a marginal increase and can therefore be seen as an unnecessary increase of the packaging dimensions. In general, the largest positive effects come from having a width larger than 1 250 mm, and a height larger than 250 mm. Therefore, if a recycler has a strategy where they address larger market shares, it is beneficial to choose an alternative larger than the X/1500/350 option. They can for example use the X/1750/350 package as a base case with the possibility to use a pallet rim to capture the largest batteries. If a recycler decides to design a smaller packaging solution, it is vital that they conduct a similar sensitivity analysis within their suggested range of dimensions to ensure they are aware of potential threshold levels and their effect on the market share.

6.3 Qualitative Evaluation

After evaluating the cost components and their sensitivity, there are still several factors that will contribute to the attractivity of offering a unified packaging solution for a battery recycler. While some aspects are required for the packaging, such as ADR compliance and the ability to be lifted by a truck, others are not seen as required, but optional. In this part of the report, five factors related to the packaging solution and their impact on the attractivity are presented, where in some cases the impact is limited to the battery recycler's internal operations while others also impact the OEM's willingness to pay. This willingness is in turn affected by several factors, for example the access to comparable packaging solutions or the value that the service provides the OEMs, which makes it hard to quantitatively estimate it. The five factors are: choice of material, sustainability impact, operational efficiency, flexibility and modularity, and lock-in effects, all illustrated in *Figure 6.8*. The evaluation for how these factors impact the attractivity for the battery recycler is therefore focused on qualitative reasoning.

Figure 6.8: Illustration of the most prominent qualitative aspects of a new packaging solution. (Source: own illustration)

Material

As discussed in the theory section about packaging development, a key decision when developing a package is the material. The material will have a large impact on how well the package functions, especially in this case when it is intended to be returnable and used for multiple cycles. The most suitable material for this packaging is likely to be either plastics, metal or wood which all have unique characteristics. Looking at these three materials, the recycler has to consider the tradeoffs of choosing one or the other. While metal is the most durable of the three, able to withstand most cycles, it is also the most expensive and heaviest. At the same time, the expensive price has to be balanced against the fact that a metal packaging is likely to have a longer lifetime, which reduces the frequency for how often new packages have to be purchased. The material weight can also have an impact on the sustainability and the handleability of the package. A heavier design leads to more non-valuable weight being transported and higher emissions, while also limiting what equipment can be used to handle the package. As for the plastic alternative, the weight and costs are lower, which will have a positive impact on the costs and environmental aspects. It is, however, a more fragile material and not inclined to last as long as metal. The same goes for wood, where there is also the risk of damage due to poor handling and exposure to bad weather leading to molded containers. These aspects all affect the performance and thereby the evaluation of a packaging solution and should be carefully investigated for the recycler to decide on the material best fitting their needs and operations.

Sustainability

One factor that could clearly be a selling point towards OEMs is sustainability. The sustainability agenda is increasingly important, pressuring organizations to improve. If investing in a more sustainable solution is possible when evaluating packaging solutions, it is likely to be preferred. For a packaging and logistics solution to be considered sustainable, it needs to be environmentally, socially, and economically sustainable.

First, to fulfill the environmental aspect, the packaging solution should be designed to have the lowest possible environmental impact. A major contributor to the environmental impact of a design is the lifetime of a unit, and the reusability possibilities. This decision is connected to the material choice, where for example a metal package is more durable, but requires more resources to be sourced and constructed compared to for example a wooden box. It is therefore a tradeoff between choosing a material with lower environmental impact but also a shorter lifetime, or a more durable material with a longer lifetime that has a higher environmental impact during its production. A second aspect of the environmental impact is the recycling possibilities of a design alternative. To close the loop for packaging material, the design of a packaging unit has to be compatible with processes involved in the recycling supply chain and have easy access to the recycling flows, reducing the friction to actually recycle. A solution should for example be easy to dismantle and separate different components and materials, and this has to be done in relative geographical proximity to a functioning recycling supply chain.

Second, when evaluating the social sustainability of a packaging and logistics solution, one important aspect is its ergonomics. An ergonomic packaging design is one that is compatible with machines to avoid manual lifts, and also a design that is easy to open and fold when empty. Another requirement from the battery recycler on the supplier should be responsible sourcing where the working conditions along the upstream supply chain are sustainable.

Lastly, the packaging also has to consider the economic sustainability which can be evaluated from different perspectives. One being the price customers have to pay in relation to the number of transport cycles the package lasts, and another being how efficient it is to utilize the truck, which results in more cost-effective transports where more EVBs are transported in one truck.

These sustainability aspects are connected to the recycler’s design decisions, but also to their sourcing situation. From a design perspective, the tradeoff between durability and low production impact has to be made in coherence with the overarching strategy of the recycler. And from a sourcing perspective, the recycler has to decide how their sourcing decision affects their sustainability footprint, and how much they are willing to invest in a more sustainable solution. These decisions do not differ between the five design alternatives investigated and can be seen as a complementary decision to the inner dimensions of the packaging solution.

Operational Efficiency

Another factor that will likely affect the OEM's willingness to pay for a packaging and logistics solution is its operational efficiency. An optimal package is therefore one that safely contains the EVB while still being convenient to handle in their internal operations. For example, a packaging design that is easy to open or one that enables stackability to easily handle multiple packs at the same time. Another design feature that has the potential to make the operations more efficient is to have it compatible for automation. Today, many OEMs heavily rely on automation and would therefore likely prefer a packaging design that fits into and supports their operations. Examples of automation compatible designs are those that help cameras locate the spatial position of the package when loading or unloading it, or RFID tags to identify where it is in the supply chain.

Another aspect of the operational efficiency is how the outer dimensions of the designs fit the processes of the OEMs and the recycler. For example, fitting one or two units on the wide side of a FTL makes a huge difference in transportation efficiency. Therefore, it is important to consider all steps in the process and evaluate how the design's qualities fit into the operations. This is relevant for all five design alternatives and is something that the recycler needs to do in coherence with the OEMs when evaluating different solutions.

Flexibility and Modularity

Another aspect is how flexible a package is to handle the variation in dimensions that EVBs offer. Flexibility can be achieved in multiple ways, but two ways that seem viable and need further exploration, are to use inserts inside of the package to fit multiple batteries in the same box, and to have an adjustable height by using pallet rims. These approaches enable a modular design that helps to efficiently pack batteries of varying sizes. A flexible package can benefit both the recycler and the OEMs, and potentially increase their willingness to pay for the solution. Flexibility benefits the recycler by allowing them to efficiently pack a variety of batteries using the same type of packaging, and the OEMs from being able to have only one service provider for all their batteries instead of having different suppliers depending on the battery size.

Lock-in Effects

A potential risk for a battery recycler when developing a new packaging is that specific design elements might lead to lock-in effects with a particular supplier. A lock-in effect could arise if the packaging supplier that developed the packaging has a patent for a superior design that makes more durable or more cost-effective material compared to its competitors. It can also occur when the recycler collaborates with a packaging supplier to design a complex solution. In this case, the supplier will likely prefer materials, functionalities, or dimensions that fit their qualities, thereby obstructing other suppliers to replicate the design, and locking in the recycler. The risk of relying only on one supplier is that the recycler might be too dependent on the other party, and thereby exposed and vulnerable to changes in, for example price. In a lock-in situation, the supplier has more control over price and other qualitative aspects of the deal, knowing that the recycler cannot afford to harm their relation.

Similar to the other qualitative aspects, collaboration with suppliers is not specific to any suggested design alternative, but an additional decision the recycler has to make. It is important that the supplier considers the strategic importance of the packaging solution, and how the design relates to their supply chain strategy. These strategic aspects are discussed in the coming chapter.

6.4 Strategic Evaluation

After addressing the quantitative and qualitative aspects it is important to evaluate how the design alternative fits into the strategic direction of the recycler. An alternative can be feasible when comparing costs and qualitative aspects, but if it does not follow the strategic direction of the recycler, it will not be a beneficial investment in the long run. This chapter discusses how different supply chain strategies differ, and how the different design alternatives and qualitative aspects fit into different strategies.

Applying Hayes and Wheelwrights' framework, presented in *2.2 Supply Chain Theory*, to the situation of an EVB recycler, two extremes can be characterized based on the efficiency and effectiveness concepts. For an efficiency focused operation, a recycler would focus on capturing a large market share, pushing high volumes, and mainly addressing cost savings. A recycler using this supply chain strategy mainly competes with a low price and needs a supply chain that can handle the larger volumes and its variability. On the other hand, a recycling operation focusing on effectiveness, the main objective is not to capture large volumes, but to deliver maximized value to their selected customer segment. They would typically specialize in subcategories on the market, ensuring a tailored solution for that particular segment. Instead of competing for price, they deliver better suited solutions and a larger customer value. Placing these stereotypes in the product-process matrix, the recycler addressing higher volumes would design an efficient supply chain strategy placing them in the bottom right corner of *Figure 6.9*. The other recycler, focusing on a niche market, would instead design its supply chain to be effective, placing it in the upper left corner of *Figure 6.9*.

Further, evaluating the different design alternatives from this strategic point of view, they can be placed in the framework using the cost calculation model previously presented. Starting with Alternative 1, by only selecting smaller EVBs, it addresses a smaller market compared to the other alternatives. This alternative can also be seen as a niche product, only targeting smaller EVBs. By offering a niche product, Alternative 1 can increase the fill rate within the packaging unit and thereby deliver more value to the customers by ensuring an efficient solution for that subgroup of the market. Therefore, Alternative 1 fits in the upper left corner in the product-process matrix with processes adjusted for lower volumes and a unique product offering to the niche market. On the other extreme, Alternative 5 captures a wider market share, and hence larger total volumes, thereby needing more streamlined processes in the recycler's supply chain. It competes with other solutions by offering a larger container, fit for a larger product variation. This decreases the operational efficiency, but it increases the total captured volume. Because of this, it does not compete with a rich value add to customers but is instead able to cut prices and compete in this aspect instead. Placing Alternative 5 in the matrix, it fits in the lower right corner together with an efficiency focused supply chain strategy. For Alternative 2, 3, and 4, they increasingly move from an effective to a more efficient solution. All alternatives are plotted in the product-process matrix in *Figure 6.9*.

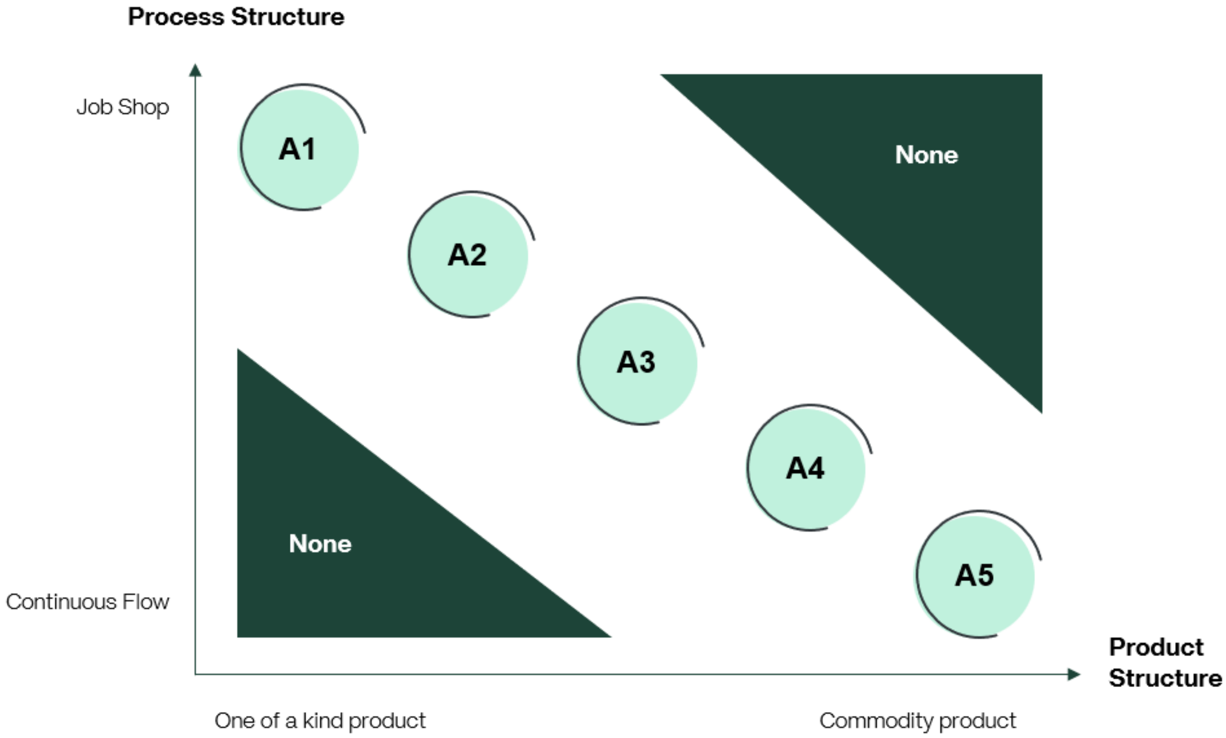


Figure 6.9: The product-process matrix presented by Hayes and Wheelwright (1979) with the different design alternatives plotted on an illustrative scale. (Own illustration)

Besides the differentiation made in the cost comparison model, the design alternatives can all have different qualitative attributes. The qualitative attributes can in general be changed regardless of the inner dimensions of the packaging solution and should therefore be seen as separate contributors to the strategic alignment. The qualitative aspects relevant for the strategic evaluation are all described in *6.3 Qualitative Evaluation*. These aspects do not always fit the matrix standing alone, however, together with the result from the cost comparison they can nudge the alternative in a given strategic direction. Starting with the choice of material, the main materials used are plastics, metal, or wood. These materials have different price points, and also affect the durability of the solution. For example, metal constructions are in general more expensive than wood, but they extend the lifetime of the product. The operational performance also affects the strategic fit. A heavily engineered packaging container fit for automation in different stages of the supply chain has a different strategic edge than a basic solution without extra functionality. Further, choice of material together with the design and operational efficiency can all contribute to the strategic performance of an alternative. Comparing a packaging solution made by recycled plastic, engineered for automation in different systems with modular components, and with a long lifetime to an alternative constructed in virgin plastic, with limited applicability and a shorter lifetime, the sustainability impact will be significantly different. Lastly, the choice of supplier and purchasing decision also affects the strategic placement of an alternative. Sourcing a packaging solution for an effective supply chain might indicate a purchasing situation where the suppliers are integrated in the design process and a closer collaboration is expected. For efficient alternatives, the sourcing is more likely to be in the form of multisourcing where the recycler applies pressure on the suppliers by driving costs down in negotiations, comparing different alternatives and keeping the lock-in effects low.

These qualitative aspects all contribute to the strategic placement of an alternative and should be used and tweaked by the recycler to achieve an optimized strategic fit between the packaging solution, its supply chain and the overarching business strategy. Combining this adjustment with a base from the cost comparison model, the recycler cannot only choose from different feasible and cost-effective solutions, they can also fine tune them according to their strategic goals.

6.5 Summary

Concluding the sixth chapter, this section highlights the key takeaways from the packaging evaluation. The evaluation included a cost comparison with operational improvements and a sensitivity analysis of the major parameters, a qualitative evaluation of the most prominent decisions for a recycler, and a strategic evaluation relating the design alternatives to different supply chain strategies. From this evaluation it is evident that the EVB recycling market can benefit from a unified packaging solution, due to the current lack of efficiency in the observed operations. Additionally, from analyzing available EVB dimensions in *5.1 Flow Analysis*, a dominant design seems to emerge which further strengthens the case for standardization and process innovation. With these insights, it can be concluded that not only is the market ready for a unified packaging solution, it also seems to be a good investment for the recyclers.

The evaluation is focused on five design alternatives derived from their inner dimensions and resulting market capture. All alternatives generate cost savings from the first year of implementation, with an average saving of 40-85% compared to the baseline case. The relative savings are generally higher for smaller solutions where the transportation can be more optimized, whereas the larger solutions have the largest total savings due to their larger volumes captured. As for joint packing, where multiple EVBs are packed into the same packaging unit when allowed, all alternatives improve by this implementation. However, most affected are the larger solution where the relative savings increase significantly. Such a positive business case enables the recycler to choose freely between the alternatives, implementing the one or the combination of alternatives best fitting their strategic needs.

When evaluating the robustness of the model and the alternatives, the thesis concludes that there is no single parameter that can drastically change the outcome, and all alternatives have enough buffer to withstand a relatively high degree of variability. From this analysis, it can generally be said that the cost- and market share parameters have a linear impact on the savings, whereas the inner dimensions are affected by threshold values where the impact on savings can change more irregularly. It is therefore important for recyclers to consider these thresholds and adapt the inner dimension to the limitations of their recycling process and its interaction points.

Further, when the quantitative aspects of the alternatives have been evaluated, the recycler has to examine a number of qualitative aspects. From the case company and the business case built around their situation, the most relevant aspects concern the choice of material, sustainability aspects, operational effects, flexibility, and modularity, as well as potential lock-in effects. These decisions can all be seen as complementary to the previously mentioned decisions on inner dimensions and thereby the targeted market share. By for example deciding on material, the recycler can decide if they want to address their market using a sturdy and expensive solution in metal, or if they want to approach it with a lighter plastic, less resistant to damage. By taking strategic decisions like these, all proposed alternatives can be tweaked to better fit the recycler's business- and supply chain strategy.

Lastly, evaluating the five alternatives from a strategic point of view, they can be separated by comparing their efficiency and effectiveness. By using Hayes and Wheelwright’s product-process matrix, the thesis concludes that a recycler pursuing a responsive supply chain strategy can benefit more from using a more niched packaging solution that addresses a smaller market share and can adapt the proposition to their customer segment. This corresponds to the smaller Alternative 1. On the other hand, Alternative 5 fits better into a strategy where a wider market is addressed, and market shares are gained by offering a more general solution adapted to more EVB types and sizes.

In conclusion, the EVB market is ready for a standardized packaging solution for OEM volumes, and the recycler can financially benefit from implementing such a solution. When choosing the best solution for a specific recycler it is important to take their strategic direction into account and align the packaging specifications accordingly. By doing this, a battery recycler can reduce large amounts of their operational costs, increase their internal efficiency, and at the same time create a stronger willingness to pay from OEMs.

7. Conclusion

This chapter concludes the thesis by summarizing the key findings and answering the research question. In addition to addressing the purpose of the thesis, the theoretical and practical contribution from the report is also discussed as well as suggestions for areas that need further research and exploration. Finally, the thesis is rounded with a reflection about the writing process.

The purpose of the thesis is to "*investigate how a battery recycler can benefit from offering a unified packaging- and logistics solution for battery recycling, how a solution could look like, and how supply chain performance will be affected by such a solution"*. To start off and get a better understanding of the subject, the purpose was met by reviewing literature related to EV batteries, supply chain theory and packaging development. This initial was followed by an in-depth case study of a company active within battery recycling to be able to draw more specific conclusions. The case study involved a quantitative evaluation where five packaging design alternatives were analyzed from a financial point of view. It also involved a qualitative part, where design features such as material and sustainability were discussed from a more general perspective. These two parts were finally complemented by a strategic discussion about how to align the packaging design to fit the organization's overarching business- and supply chain strategy.

Further discussion about the key findings and their implications for the research question and objectives follows in the upcoming subchapters.

7.1 Answering the Research Question and Research Objectives

The purpose of the thesis is addressed by answering the three posed research objectives and the research question posed in *1.3 Purpose and Research Question*. Starting with RO1 - mapping the resources and conditions needed to support a standardized packaging solution - chapter 4, 5, and 6 illuminates some major aspects affecting the viability of the proposed solution. First, the packaging solution has to be safe and compliant with the road transportation regulation ADR. It also has to fit the addressed market share, which most likely are flat battery packs. In addition, the packaging solution is preferably reusable and recyclable to comply with the increasing sustainability demand from both consumers and OEMs. Lastly, the solution has to be economically viable for the recycler. As for the conditions needed to support a standardized solution, the recycler needs a start capital for the initial material investment, a functioning supply chain for OEM flows including transportation, handling, and storing operation. The recycler also needs to establish a return flow of packaging units, as well as a process for recycling the units when they reach the end of life.

By addressing the needed resources and conditions, RO2 could also be answered. The research objective addressed potentially restrictive aspects of a packaging solution, and these turned out to be the same aspects needed for it to be viable. For example, the solution needs to follow the ADR regulations to be a viable solution, this leads to an inherited limitation stating that all solutions need to be within the frame of ADR.

As for RO3, - suggest a viable supply chain setup in the mapped solution space - all five presented alternatives are considered viable solutions and seem profitable based on the financial evaluation. Each alternative also needs to be complemented by strategic decisions specific to each recycler to be implemented from a practical point of view. When conducting the sensitivity analysis, these strategic decisions can affect the relative savings from each solution. However, all alternatives have a significant buffer in their potential savings, making it unlikely that such a strategic decision will make the alternative unprofitable.

RQ: *How can a battery recycler benefit from offering a unified packaging- and logistics solution for battery recycling?*

Lastly, addressing the research question, the thesis concludes that a battery recycler can benefit from implementing a unified packaging solution for OEM flow, given that the solution follows the recycler's overarching strategy. By implementing a packaging unit that is aligned with the business strategy and thereby able to keep operations running, a unified solution can lead to significant cost savings for the recycler. By designing the solution to also fit the qualitative needs from OEMs, it also has the potential to lead to an increased willingness to pay from the OEMs, figuring as an unique selling point for the recycler.

7.2 Theoretical Contribution

The thesis contributes to the field of supply chain theory by combining it with packaging logistics and the theory of electric vehicle batteries. This is done by applying previously known theory to a new holistic single case study. The study concludes the market's current state maturity and connects it to the emerging process innovation in the form of a new unified packaging solution. Additionally, the study also contributes to theory by building and applying an evaluation framework for packaging solutions addressing EV battery packs, illustrating its relevance by connecting it to the case company. By submitting this thesis, the connection between supply chain theory, packaging theory, and the booming EV market becomes more explored and integrated.

7.3 Practical Contribution

For the practical contribution, this thesis provides EVB recyclers with a comprehensive description of requirements and limitations for their packaging solutions for OEM flows in Europe. It also provides a framework for evaluating the potential cost savings from a suggested packaging solution, as well as an illustrative example of five different solutions and how they fit different business- and supply chain strategies. More specifically, the thesis provides the case company with an overview of the benefits of implementing unified packaging solutions, as well as an example of how the potential of these solutions can be evaluated.

7.4 Limitations and Future Research

This thesis is focused on framing the conditions in which a unified solution can be beneficial for an EVB recycler, and how such a solution can take form and be evaluated. However, due to time restrictions some interesting parts have been left for further research. First, this study is based on one case company, its abilities and limitations. To further develop the study, multiple case studies could lead to more developed and nuanced insights on market trends and packaging requirements.

Another interesting extension of the study would be to structure and evaluate the implementation of a unified packaging solution. This thesis is explorative, expanding on different ideas for packaging designs and how it can affect an EVB recycler. But it does not cover the implementation plan, sales approach towards OEMs, internal organizations, nor does it provide a plan for performance evaluation when a packaging solution is implemented. Another operational aspect worth exploring is the possibility of implementing a combination of multiple packaging solutions, building a portfolio of logistic solutions addressed for a recycler’s given market share. These aspects are all interesting extensions with the potential of illuminating further learning in the area.

Further, the presented thesis and models can be extended by adding more complex assumptions and conditions. Some interesting extensions and research questions suggested for further research are:

- How will increasing second life applications impact the case for battery recycling?
- Is it possible to move discharging and crushing of EVBs to the OEM site to avoid the heavily regulated transportation of charged batteries?
- What will the sourcing network look like in the future? Will EOL EVBs be collected from OEMs, scrap yards, car dealerships, local repair stores etc.?

By adding these assumptions to the model, the business case for EVB recycling can both be threatened by more batteries going to second life applications, but also more attractive by developing the service by offering customers discharging and crushing at their site. By bringing these operations upstream in the supply chain, the transport from OEM to the recycling sites becomes less complex and could potentially make a more profitable case for the recycler. However, these ideas are left unexplored and for future research to investigate.

7.5 Concluding Reflections

Concluding this thesis, we would like to reflect on the process of writing it, investigating the packaging and logistics situation of the case company, and combining it with theory.

During the process our understanding of both supply chain and packaging theory, its applications, and the EVB market have increased. The learning process was initiated by an intro period where we were introduced to the case company, their ambitions with the project, and also the challenges they faced with their current operations. This phase of the thesis was extremely valuable for us, and ultimately set the tone for the resulting investigations. By ensuring our understanding of the subject and context we were able to formulate a research question and project plan that was robust and closely connected to the purpose of the thesis. In hindsight, this was instrumental for our understanding and reduced the risk for scope creep drastically.

After the initial phase of understanding the purpose and core problem, the process was highly iterative since the thesis has an explorative nature. This meant that we had to work to adjust after the information we got from the case company, and that at any time new information could arise and change the course of the thesis. This setup was challenging and developing, forcing us to always have the purpose in mind and focus on the main objective. With this said, the interviews and fact-finding phase did not only develop our understanding of the market and supply chain theory, but it also developed our skills as project leaders and co-workers.

Finally, we believe that this thesis will help the case company continue their journey of process innovation, contribute to academia by applying theory to an emerging and ever-changing market, as well as develop us as professionals.

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9. Appendix

9.1 Appendix A: Interview guide

In this appendix the interview questions are presented.

9.1.1 Business Analyst at Case Company

How will the market for recycling EVBs grow in the future?

How is the relation between modules and packs expected to develop in the future?

How does EVB volumes differ between OEMs, now and in future market projections?

Can you look at the most sold EVs in the last five years and use the distribution from them to model the future inflow for battery recycling?

Do you see any trends in the size of packs and modules? Are they getting larger or smaller?

Are there any other tech trends that will affect a packaging or logistics solution you see in the future?

9.1.2 Lead Logistics and Planning Developer at Case Company

What transportation mode will be used for the recycling operation?

Why do OEMs keep battery information confidential?

Where does the need for recycling occur in the OEM processes?

Who manages the transportation of EVBs and what payment terms apply?

What are important KPIs for the logistics operation?

How does variability in sourcing affect the logistics operation?

Is the data sample of battery sizes representative for the current EVB market?

What packaging solutions are used today?

How does the logistics for packs and modules differ?

How will the future market for EVB develop?

9.1.3 Project Manager at Case Company

Where can we find information on battery sizes from OEMs?

Why do OEMs keep battery information confidential?

What packaging solutions are used today?

How does the logistics for packs and modules differ?

9.1.4 Director of Recycling Expansion at Case Company

What transportation mode will be used for the recycling operation?

How large share of the recycled EVB flow is green, yellow, and red?

9.1.5 Warehouse Manager at Case Company

What is the process for managing incoming EVBs for recycling?

How do you handle EVB packages?

What are the biggest bottlenecks in your current operations?

What volumes are you managing today?

From what sources are you receiving EVBs today?

What features in the packaging solution would improve your processes today?

Are there any benefits of using the same packaging solution for transportation and internal handling of the EVB?

How do you manage the return of packaging material?

Who is responsible for, and owns, the packaging solutions today?

9.1.6 Transportation Expert at Case Company

What rules apply to the transportation of used or damaged EVBs?

Does the regulation differ between countries or regions?

How do the regulations differ between transportation modes?

What is the difference between hazardous waste and dangerous goods regulations?

What rules apply to the storing of batteries?

Do you have internal regulations at the company?

How do you classify different degrees of damage for used EVBs?

Can transportation regulations be interpreted in different ways?

How do you, at the case company, interpret the EVB regulations?

9.1.7 Senior Supply Chain Consultant Simon Theißen

How can you forecast revenue for a business case when the product is unknown?

What KPIs are relevant for packaging solutions?

What costs are usually included in a packaging business case?

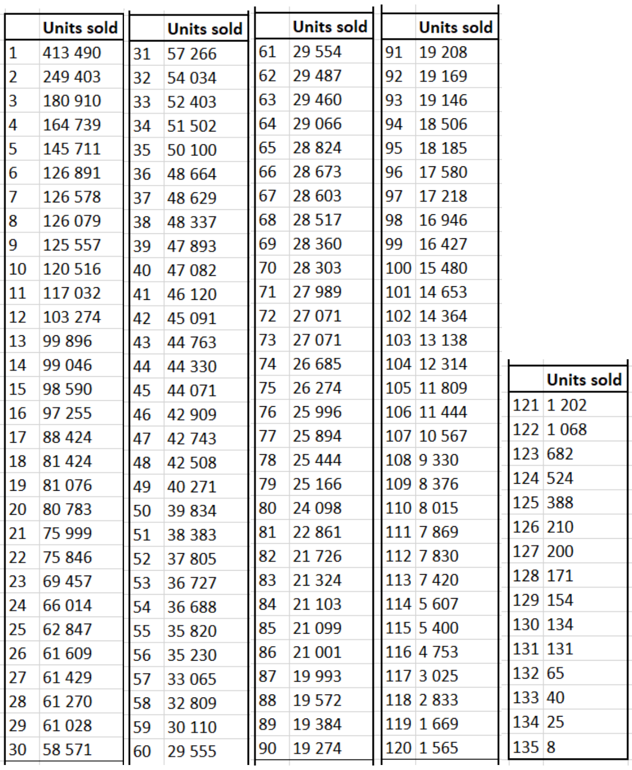
The case is built on assumptions that might be subject to change, how can we make it as reliable and future proof as possible?

How do you manage high sourcing variability?

We know the market is rapidly growing and the solution we are looking into is aimed at fitting the future market as well. Today, the only indicator of future volumes, as we see it, are qualitative market trends. How should we incorporate them in the business case?

9.2 Appendix B: Most Sold EVs

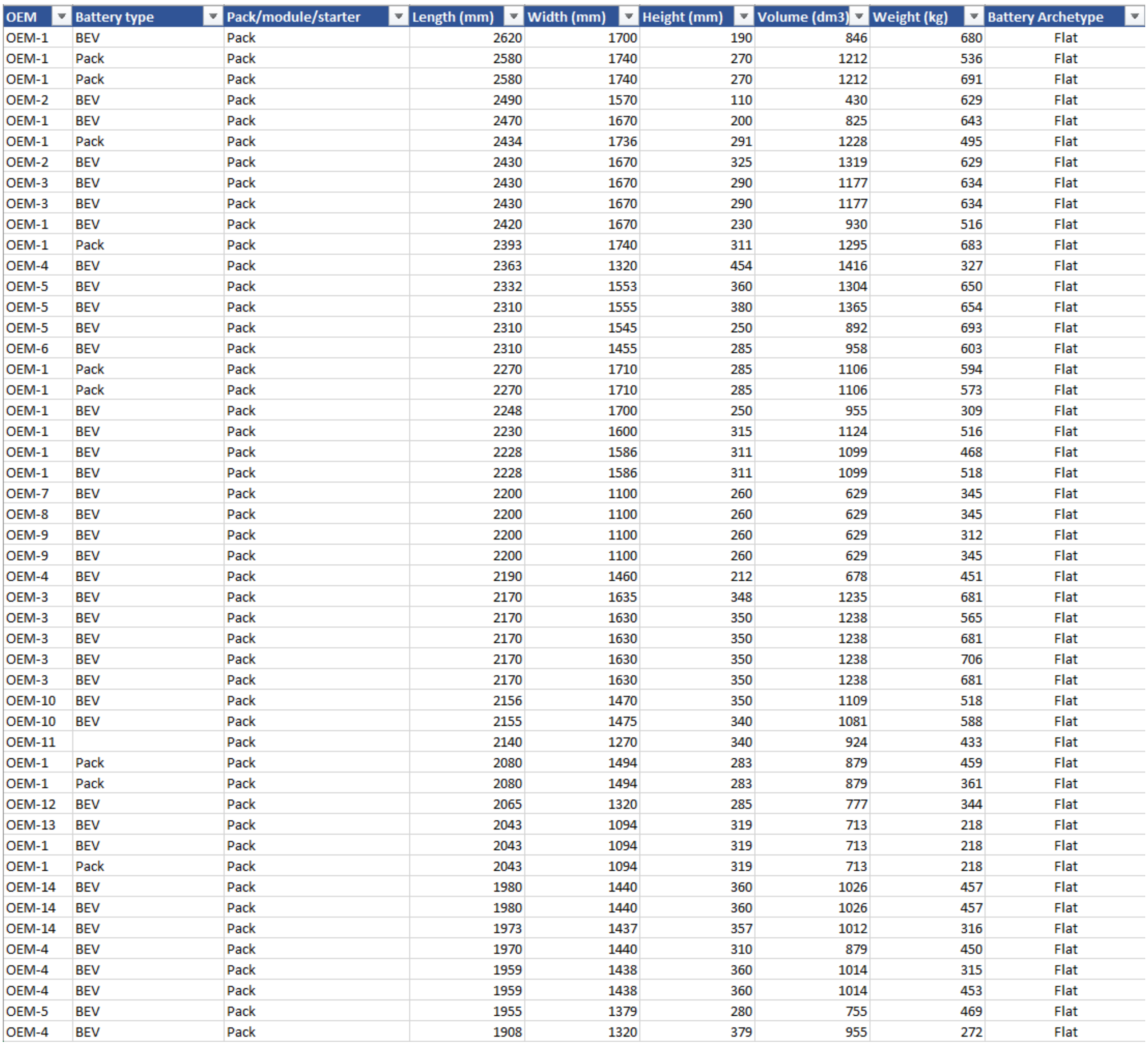
The list covers the top 135 most sold EVs (both BEV and PHEV) during the period 2019-2022. The statistics are used in section *4.2.2 Product Flow* (Jato, 2022; CarSalesBase, 2020; CarSalesBase, 2022)



	Units sold
1	413 490
2	249 403
3	180 910
4	164 739
5	145 711
6	126 891
7	126 578
8	126 079
9	125 557
10	120 516
11	117 032
12	103 274
13	99 896
14	99 046
15	98 590
16	97 255
17	88 424
18	81 424
19	81 076
20	80 783
21	75 999
22	75 846
23	69 457
24	66 014
25	62 847
26	61 609
27	61 429
28	61 270
29	61 028
30	58 571
31	57 266
32	54 034
33	52 403
34	51 502
35	50 100
36	48 664
37	48 629
38	48 337
39	47 893
40	47 082
41	46 120
42	45 091
43	44 763
44	44 330
45	44 071
46	42 909
47	42 743
48	42 508
49	40 271
50	39 834
51	38 383
52	37 805
53	36 727
54	36 688
55	35 820
56	35 230
57	33 065
58	32 809
59	30 110
60	29 555
61	29 554
62	29 487
63	29 460
64	29 066
65	28 824
66	28 673
67	28 603
68	28 517
69	28 360
70	28 303
71	27 989
72	27 071
73	27 071
74	26 685
75	26 274
76	25 996
77	25 894
78	25 444
79	25 166
80	24 098
81	22 861
82	21 726
83	21 324
84	21 103
85	21 099
86	21 001
87	19 993
88	19 572
89	19 384
90	19 274
91	19 208
92	19 169
93	19 146
94	18 506
95	18 185
96	17 580
97	17 218
98	16 946
99	16 427
100	15 480
101	14 653
102	14 364
103	13 138
104	12 314
105	11 809
106	11 444
107	10 567
108	9 330
109	8 376
110	8 015
111	7 869
112	7 830
113	7 420
114	5 607
115	5 400
116	4 753
117	3 025
118	2 833
119	1 669
120	1 565
121	1 202
122	1 068
123	682
124	524
125	388
126	210
127	200
128	171
129	154
130	134
131	131
132	65
133	40
134	25
135	8

9.3 Appendix C: Battery Models

The appendix includes data over car models and the dimensions of their batteries.



OEM	Battery type	Pack/module/starter	Length (mm)	Width (mm)	Height (mm)	Volume (dm3)	Weight (kg)	Battery Archetype
OEM-1	BEV	Pack	2620	1700	190	846	680	Flat
OEM-1	Pack	Pack	2580	1740	270	1212	536	Flat
OEM-1	Pack	Pack	2580	1740	270	1212	691	Flat
OEM-2	BEV	Pack	2490	1570	110	430	629	Flat
OEM-1	BEV	Pack	2470	1670	200	825	643	Flat
OEM-1	Pack	Pack	2434	1736	291	1228	495	Flat
OEM-2	BEV	Pack	2430	1670	325	1319	629	Flat
OEM-3	BEV	Pack	2430	1670	290	1177	634	Flat
OEM-3	BEV	Pack	2430	1670	290	1177	634	Flat
OEM-1	BEV	Pack	2420	1670	230	930	516	Flat
OEM-1	Pack	Pack	2393	1740	311	1295	683	Flat
OEM-4	BEV	Pack	2363	1320	454	1416	327	Flat
OEM-5	BEV	Pack	2332	1553	360	1304	650	Flat
OEM-5	BEV	Pack	2310	1555	380	1365	654	Flat
OEM-5	BEV	Pack	2310	1545	250	892	693	Flat
OEM-6	BEV	Pack	2310	1455	285	958	603	Flat
OEM-1	Pack	Pack	2270	1710	285	1106	594	Flat
OEM-1	Pack	Pack	2270	1710	285	1106	573	Flat
OEM-1	BEV	Pack	2248	1700	250	955	309	Flat
OEM-1	BEV	Pack	2230	1600	315	1124	516	Flat
OEM-1	BEV	Pack	2228	1586	311	1099	468	Flat
OEM-1	BEV	Pack	2228	1586	311	1099	518	Flat
OEM-7	BEV	Pack	2200	1100	260	629	345	Flat
OEM-8	BEV	Pack	2200	1100	260	629	345	Flat
OEM-9	BEV	Pack	2200	1100	260	629	312	Flat
OEM-9	BEV	Pack	2200	1100	260	629	345	Flat
OEM-4	BEV	Pack	2190	1460	212	678	451	Flat
OEM-3	BEV	Pack	2170	1635	348	1235	681	Flat
OEM-3	BEV	Pack	2170	1630	350	1238	565	Flat
OEM-3	BEV	Pack	2170	1630	350	1238	681	Flat
OEM-3	BEV	Pack	2170	1630	350	1238	706	Flat
OEM-3	BEV	Pack	2170	1630	350	1238	681	Flat
OEM-10	BEV	Pack	2156	1470	350	1109	518	Flat
OEM-10	BEV	Pack	2155	1475	340	1081	588	Flat
OEM-11		Pack	2140	1270	340	924	433	Flat
OEM-1	Pack	Pack	2080	1494	283	879	459	Flat
OEM-1	Pack	Pack	2080	1494	283	879	361	Flat
OEM-12	BEV	Pack	2065	1320	285	777	344	Flat
OEM-13	BEV	Pack	2043	1094	319	713	218	Flat
OEM-1	BEV	Pack	2043	1094	319	713	218	Flat
OEM-1	Pack	Pack	2043	1094	319	713	218	Flat
OEM-14	BEV	Pack	1980	1440	360	1026	457	Flat
OEM-14	BEV	Pack	1980	1440	360	1026	457	Flat
OEM-14	BEV	Pack	1973	1437	357	1012	316	Flat
OEM-4	BEV	Pack	1970	1440	310	879	450	Flat
OEM-4	BEV	Pack	1959	1438	360	1014	315	Flat
OEM-4	BEV	Pack	1959	1438	360	1014	453	Flat
OEM-5	BEV	Pack	1955	1379	280	755	469	Flat
OEM-4	BEV	Pack	1908	1320	379	955	272	Flat

OEM-1	Pack	Pack	1880	1706	342	1097	215	Flat
OEM-1	Pack	Pack	1880	1706	342	1097	200	Flat
OEM-15	BEV	Pack	1835	1445	355	941	493	Flat
OEM-16	BEV(82kWh)	Pack	1830	1450	150	398	485	Flat
OEM-9	BEV	Pack	1830	1450	150	398	485	Flat
OEM-14	BEV	Pack	1830	1150	300	631	286	Flat
OEM-9	BEV	Pack	1820	1452	182	481	503	Flat
OEM-3	BEV	Pack	1820	1450	190	501	491	Flat
OEM-3	BEV	Pack	1820	1450	190	501	491	Flat
OEM-17	BEV	Pack	1820	1450	140	369	493	Flat
OEM-9	BEV	Pack	1760	1130	340	676	246	Flat
OEM-18	BEV	Pack	1705	1415	176	425	220	Flat
OEM-17	BEV	Pack	1680	1100	330	610	229	Flat
OEM-8	BEV	Pack	1680	1100	330	610	234	Flat
OEM-9	BEV	Pack	1680	1100	330	610	229	Flat
OEM-1	HEV	Pack	1660	964	174	278	276	Flat
OEM-1	Pack	Pack	1659.5	964	174	278	233	Flat
OEM-1	Pack	Pack	1659.5	964	174	278	265	Flat
OEM-19	BEV	Pack	1625	1051	300	512	236	Flat
OEM-20	BEV	Pack	1625	1051	300	512	236	Flat
OEM-12	BEV	Pack	1625	1051	300	512	236	Flat
OEM-21	BEV	Pack	1600	1265	330	668	322	Flat
OEM-1	Pack	Pack	1592	1298	284	587	250	Flat
OEM-22	BEV	Pack	1540	1140	265	465	304	Flat
OEM-1	Pack	Pack	1511	535	196	158	85	Tunnel
OEM-20	PHEV	PHEV Pack	1505	1005	250	378	180	Flat
OEM-20	PHEV	PHEV Pack	1505	1005	250	378	180	Flat
OEM-1	PHEV	PHEV Pack	1500	1400	140	294	172	Flat
OEM-4	PHEV	PHEV Pack	1500	940	250	353	138	Flat
OEM-1	Pack	Pack	1495	1380	165	340	172	Flat
OEM-9	BEV	Pack	1470	1440	130	275	377	Flat
OEM-1	Pack	Pack	1460	305	330	147	98	Tunnel
OEM-1	Pack	Pack	1460	305	330	147	104	Tunnel
OEM-23	PHEV	PHEV Pack	1400	440	500	308	125	Tunnel
OEM-24	PHEV	PHEV Pack	1300	750	300	293	255	Tunnel
OEM-1	Module	Module	1300	420	85	46	76	
OEM-1	Module	Module	1300	420	85	46	76	
OEM-1	Module	Module	1300	420	85	46	76	
OEM-1	Module	Module	1300	420	85	46	76	
OEM-1	Module	Module	1295	373	86	42	83	
OEM-1	PHEV	PHEV Pack	1255	1246	276	432	227	Flat
OEM-4	PHEV	PHEV Pack	1237	367	266	121	56	Tunnel
OEM-14	PHEV	PHEV Pack	1237	366	266	120	56	Tunnel
OEM-14	PHEV	PHEV Pack	1237	366	266	120	56	Tunnel
OEM-14	PHEV	PHEV Pack	1237	366	266	120	56	Tunnel
OEM-4	HEV	Pack	1237	354	266	116	33	Tunnel
OEM-14	HEV	PHEV Pack	1210	362	225	99	33	Tunnel
OEM-4	HEV	Pack	1210	354	266	114	33	Tunnel
OEM-1	PHEV	PHEV Pack	1200	1180	260	368	NA	Flat
OEM-5	PHEV	PHEV Pack	1172	538	206	130	148	Tunnel

OEM-5	PHEV	PHEV Pack	1170	980	250	287	286	Flat
OEM-1	PHEV	PHEV Pack	1134	541	271	166	113	Tunnel
OEM-1	HEV	Pack	1134	541	271	166	119	Tunnel
OEM-1	Pack	Pack	1134	541	271	166	117	Tunnel
OEM-1	Pack	Pack	1134	541	271	166	118	Tunnel
OEM-1	Pack	Pack	1130	540	270	165	126	Tunnel
OEM-1	PHEV	PHEV Pack	1110	640	280	199	124	Tunnel
OEM-25	PHEV	PHEV Pack	1102	583	195	125	178	Tunnel
OEM-25	PHEV	PHEV Pack	1102	583	195	125	178	Tunnel
OEM-25	PHEV	PHEV Pack	1102	583	195	125	178	Tunnel
OEM-25	PHEV	PHEV Pack	1102	583	195	125	178	Tunnel
OEM-25	PHEV	PHEV Pack	1100	655	200	144	149	Tunnel
OEM-5	PHEV	PHEV Pack	1060	615	123	80	100	Tunnel
OEM-5	PHEV	PHEV Pack	1060	615	123	80	100	Tunnel
OEM-1	PHEV	PHEV Pack	1050	580	360	219	115	Tunnel
OEM-9	HEV	Pack	1050	500	200	105	53	Tunnel
OEM-26	HEV	Pack	1041	558	245	142	40	Tunnel
OEM-14	PHEV	PHEV Pack	1035	739	238	182	59	Tunnel
OEM-14	PHEV	PHEV Pack	1035	739	238	182	59	Tunnel
OEM-14	PHEV	PHEV Pack	1035	739	238	182	59	Tunnel
OEM-4	PHEV	PHEV Pack	1035	596	242	149	59	Tunnel
OEM-3	PHEV	PHEV Pack	1030	810	240	200	141	Flat
OEM-3	PHEV	PHEV Pack	1030	810	240	200	141	Flat
OEM-3	PHEV	PHEV Pack	1030	810	240	200	141	Flat
OEM-9	PHEV	PHEV Pack	1020	690	240	169	117	Tunnel
OEM-3	PHEV	PHEV Pack	1020	630	270	174	210	Tunnel
OEM-3	PHEV	PHEV Pack	1020	630	270	174	210	Tunnel
OEM-14	PHEV	PHEV Pack	1004	938	134	126	64	Flat
OEM-3	PHEV	PHEV Pack	990	690	240	164	153	Small flat
OEM-3	PHEV	PHEV Pack	990	690	240	164	153	Small flat
OEM-3	PHEV	PHEV Pack	990	690	240	164	153	Small flat
OEM-1	Module	Module	982.8	352.4	120	42	68	
OEM-3	PHEV	PHEV Pack	980	800	240	188	138	Small flat
OEM-3	PHEV	PHEV Pack	980	800	240	188	138	Small flat
OEM-3	PHEV	PHEV Pack	950	710	250	169	120	Small flat
OEM-17	PHEV	PHEV Pack	950	620	250	147	135	Small flat
OEM-17	PHEV	PHEV Pack	950	620	250	147	135	Small flat
OEM-7	PHEV	PHEV Pack	950	620	250	147	124	Small flat
OEM-17	PHEV	PHEV Pack	950	620	250	147	135	Small flat
OEM-9	PHEV	PHEV Pack	950	620	250	147	130	Small flat
OEM-9	PHEV	PHEV Pack	950	620	250	147	120	Small flat
OEM-9	PHEV	PHEV Pack	950	620	250	147	124	Small flat
OEM-3	PHEV	PHEV Pack	950	610	260	151	130	Small flat
OEM-3	PHEV	PHEV Pack	950	610	260	151	130	Small flat
OEM-3	PHEV	PHEV Pack	950	610	260	151	130	Small flat
OEM-9	PHEV	PHEV Pack	950	610	240	139	120	Small flat
OEM-14	PHEV	PHEV Pack	940	310	219	64	64	Small other
OEM-4	FCEV	Pack	937	646	207	125	53	Small flat
OEM-4	FCEV	Pack	926	830	280	215	45	Small flat
OEM-5	PHEV	PHEV Pack	915	520	200	95	114	Small flat

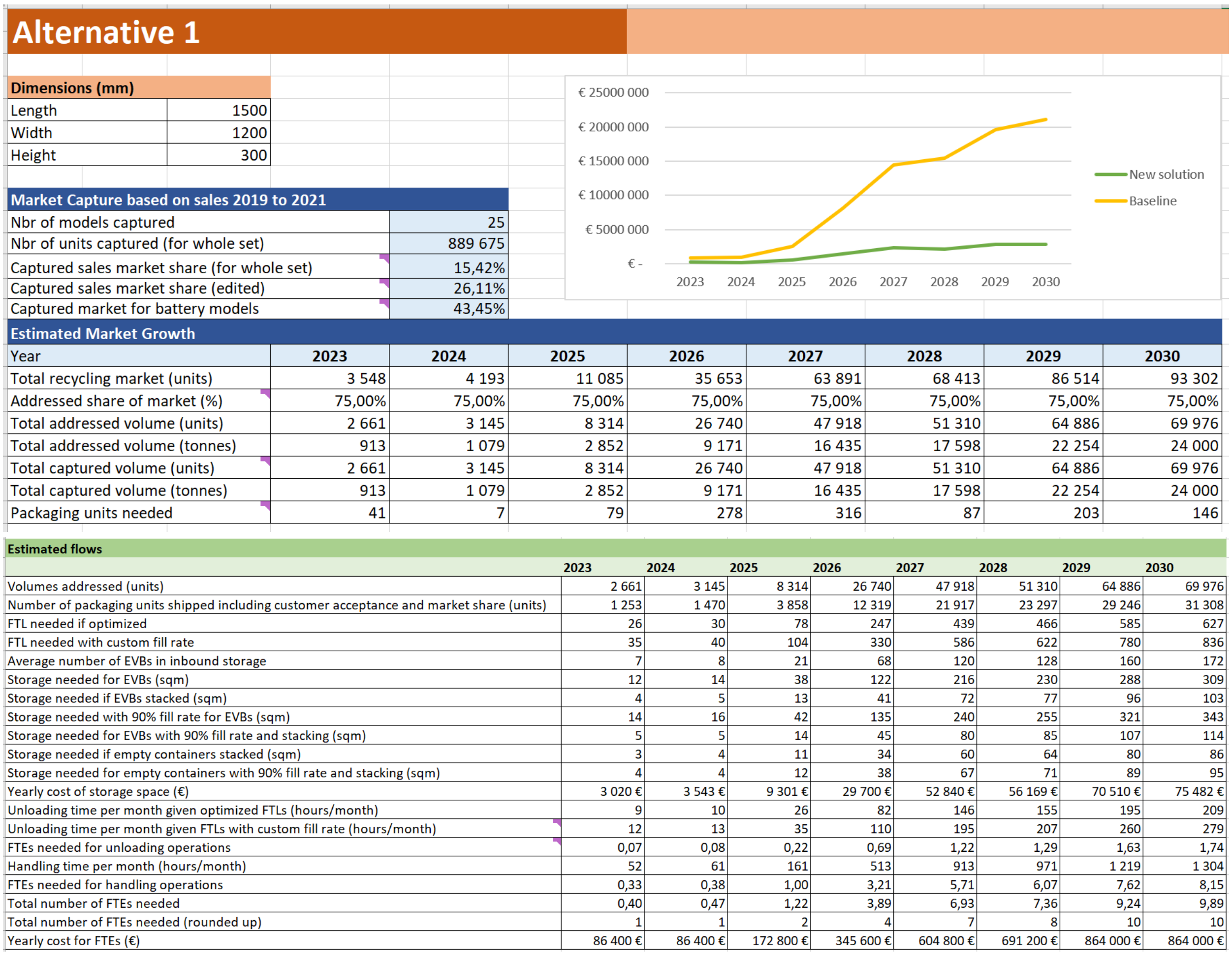
OEM-5	PHEV	PHEV Pack	915	520	200	95	114	Small flat
OEM-5	PHEV	PHEV Pack	915	520	200	95	114	Small flat
OEM-5	PHEV	PHEV Pack	915	520	200	95	114	Small flat
OEM-5	PHEV	PHEV Pack	915	520	200	95	114	Small flat
OEM-5	PHEV	PHEV Pack	915	520	200	95	114	Small flat
OEM-5	PHEV	PHEV Pack	900	480	200	86	120	Small other
OEM-5	PHEV	PHEV Pack	900	480	200	86	120	Small other
OEM-5	PHEV	PHEV Pack	900	480	200	86	120	Small other
OEM-5	PHEV	PHEV Pack	900	480	200	86	114	Small other
OEM-5	PHEV	PHEV Pack	900	480	200	86	120	Small other
OEM-14	HEV	Pack	897	441	291	115	40	Small other
OEM-5	PHEV	PHEV Pack	895	475	200	85	114	Small other
OEM-5	PHEV	PHEV Pack	895	475	200	85	114	Small other
OEM-27	PHEV	PHEV Pack	895	475	200	85	114	Small other
OEM-5	PHEV	PHEV Pack	895	475	200	85	114	Small other
OEM-14	PHEV	PHEV Pack	872	498	288	125	62	Small other
OEM-3	PHEV	PHEV Pack	870	530	240	111	143	Small flat
OEM-3	PHEV	PHEV Pack	870	530	240	111	141	Small flat
OEM-3	PHEV	PHEV Pack	870	530	240	111	143	Small flat
OEM-3	PHEV	PHEV Pack	870	530	240	111	141	Small flat
OEM-3	PHEV	PHEV Pack	870	530	240	111	141	Small flat
OEM-9	PHEV	PHEV Pack	870	510	240	106	141	Small flat
OEM-14	PHEV	PHEV Pack	856	650	307	171	62	Small flat
OEM-14	HEV	Pack	854	470	255	102	39	Small other
OEM-1	PHEV	PHEV Pack	827	769	319	203	88	Small flat
OEM-1	Pack	Pack	784	645	306	155	115	Small flat
OEM-1	PHEV	PHEV Pack	781	508	287	114	105	Small flat
OEM-28	mHEV	Pack	780	500	230	90	25	Small flat
OEM-2	PHEV	PHEV Pack	754	550	262	109	146	Small flat
OEM-2	PHEV	PHEV Pack	754	550	262	109	146	Small flat
OEM-2	PHEV	PHEV Pack	754	550	262	109	146	Small flat
OEM-2	PHEV	PHEV Pack	754	550	262	109	146	Small flat
OEM-2	PHEV	PHEV Pack	754	550	262	109	146	Small flat
OEM-1	Pack	Pack	750	715	270	145	88	Small flat
OEM-1	Module	Module	733.65	351.7	113	29	49	
OEM-13	PHEV	PHEV Pack	705	581	379	155	90	Not assigned
OEM-13	PHEV	PHEV Pack	705	581	379	155	90	Not assigned
OEM-1	PHEV	PHEV Pack	705	581	379	155	90	Not assigned
OEM-1	PHEV	PHEV Pack	705	581	379	155	87	Not assigned
OEM-3	HEV	Pack	660	430	160	45	37	Small other
OEM-1	Pack	Pack	655	494	375	121	90	Not assigned
OEM-1	Pack	Pack	637	577	378	139	91	Not assigned
OEM-1	Module	Module	596.2	351.7	113	24	38	
OEM-9	module	Module	580	230	100	13	31	
OEM-2	module	Module	461	185	164	14	23	
OEM-9	PHEV	PHEV Pack	460	410	460	87	68	Not assigned
OEM-1	Module	Module	448.8	178.2	112	9	14	
OEM-1	Module	Module	448.8	205.7	178	16	28	
OEM-1	Module	Module	440	180	105	8	13	
OEM-21	mHEV	Pack	430	150	180	12	16	Small other

OEM-5	Start	Starter Battery	413	185	203	16	21	
OEM-5	Start	Starter Battery	413	185	203	16	21	
OEM-5	Start	Starter Battery	413	185	203	16	21	
OEM-5	Start	Starter Battery	413	185	203	16	21	
OEM-14	Start	Starter Battery	410	287	118	14	13	
OEM-4	Start	Starter Battery	410	287	118	14	13	
OEM-2	module	Module	405	151	109	7	13	
OEM-2	module	Module	405	151	109	7	13	
OEM-2	module	Module	405	151	109	7	13	
OEM-2	module	Module	405	151	109	7	13	
OEM-3	mHEV	Pack	400	180	110	8	9	Small other
OEM-9	mHEV	Pack	400	180	110	8	9	Small other
OEM-5	Start	Starter Battery	397	213	235	20	23	
OEM-1	PHEV	PHEV Pack	395	265	180	19		Small other
OEM-2	module	Module	390.8	152	108	6	16	
OEM-5	Start	Starter Battery	379	213	235	19	23	
OEM-1	Module	Module	372	179	106	7	13.25	
OEM-1	Module	Module	370	180	105	7	13	
OEM-1	Pack	Pack	370	222	234	19	30	Small other
OEM-5	Start	Starter Battery	366	220	220	18	25	
OEM-9	module	Module	350	150	110	6	11.2	
OEM-9	module	Module	350	150	110	6	10.1	
OEM-9	module	Module	350	150	110	6	5.5	
OEM-9	module	Module	350	150	110	6	10.3	
OEM-5	Start	Starter Battery	345	185	195	12	23	
OEM-5	Start	Starter Battery	345	185	195	12	23	
OEM-5	Start	Starter Battery	345	185	195	12	23	
OEM-5	Start	Starter Battery	287	175	155	8	12.5	
OEM-5	Start	Starter Battery	287	175	155	8	12.5	
OEM-5	Start	Starter Battery	287	175	155	8	12.5	
OEM-2	Starter battery	Starter Battery	278	175	190	9	9	
OEM-2	Starter battery	Starter Battery	278	175	190	9	9	
OEM-2	Starter battery	Starter Battery	278	175	190	9	9	
OEM-2	Starter battery	Starter Battery	278	175	190	9	9	
OEM-5	Start	Starter Battery	278	175	155	8	12.5	
OEM-5	Start	Starter Battery	278	175	155	8	12.5	
OEM-5	Start	Starter Battery	278	175	195	9	15.5	
OEM-2	Start	Starter Battery	278	175	190	9	9	
OEM-14	Start	Starter Battery	256	170	75	3	5	
OEM-3	SCRAP		230	180	110	5	2.7	
OEM-29	mHEV	Pack	202	178	84	3	2.6	Small other
OEM-29	mHEV	Pack	202	178	84	3	2.6	Small other
OEM-29	mHEV	Pack	202	178	84	3	2.6	Small other
OEM-3	mHEV	Pack	180	110	190	4	3.8	Small other
OEM-30	PHEV	PHEV Pack	0	0		0	152	
OEM-30	PHEV	PHEV Pack	0	0		0	130	
OEM-30	mHEV	Pack	0	0		0	16	
OEM-1	PHEV	PHEV Pack	0	0	0	0	NA	
OEM-31	BEV	Pack	0	0		0		
OEM-10	BEV	Pack	0	0		0		

OEM-32	BEV	Pack	0	0		0		
OEM-33	BEV	Pack	0	0		0		
OEM-31	BEV	Pack	0	0		0		
OEM-34	BEV	Pack	0	0		0		
OEM-10	BEV	Pack	0	0		0		
OEM-11	BEV	Pack	0	0		0		
OEM-35	BEV	Pack	0	0		0		
OEM-33	BEV	Pack	0	0		0		
OEM-34	BEV	Pack	0	0		0		
OEM-31	BEV	Pack	0	0		0		
OEM-36	BEV	Pack	0	0		0		
OEM-11	HEV	Pack	0	0		0		
OEM-37	BEV	Pack	0	0		0		
OEM-18	HEV	Pack	0	0		0		
OEM-31	BEV	Pack	0	0		0		
OEM-38	BEV	Pack	0	0		0		
OEM-2	HEV	Pack	0	0		0		
OEM-39	BEV	Pack	0	0		0		
OEM-35	BEV	Pack	0	0		0		
OEM-40	BEV	Pack	0	0		0		
OEM-31	BEV	Pack	0	0		0		
OEM-41	BEV	Pack	0	0		0		
OEM-31	HEV	Pack	0	0		0		
OEM-11	HEV	Pack	0	0		0		
OEM-39	PHEV	PHEV Pack	0	0		0		
OEM-39	BEV	Pack	0	0		0		
OEM-11	HEV	Pack	0	0		0		
OEM-1	HEV	Pack	0	0		0		
OEM-39	PHEV	PHEV Pack	0	0		0		
OEM-42	BEV	Pack	0	0		0		
OEM-31	HEV	Pack	0	0		0		
OEM-31	BEV	Pack	0	0		0		
OEM-1	PHEV	PHEV Pack	0	0		0		
OEM-1	PHEV	PHEV Pack	0	0		0		
OEM-30	mHEV	Pack	0	0	0	0	16	
OEM-30	PHEV	PHEV Pack	0	0	0	0	130	
OEM-30	PHEV	PHEV Pack	0	0	0	0	152	
OEM-10	BEV	Pack	0	0	0	0		
OEM-10	BEV	Pack	0	0	0	0		

9.4 Appendix D: Financial Model in Excel

The appendix presents a snapshot from the financial model created in Excel. It is described in detail in chapter *3.4 Data Analysis and Evaluation*.



Alternative 1

Dimensions (mm)	
Length	1500
Width	1200
Height	300

Market Capture based on sales 2019 to 2021	
Nbr of models captured	25
Nbr of units captured (for whole set)	889 675
Captured sales market share (for whole set)	15,42%
Captured sales market share (edited)	26,11%
Captured market for battery models	43,45%

Estimated Market Growth

Year	2023	2024	2025	2026	2027	2028	2029	2030
Total recycling market (units)	3 548	4 193	11 085	35 653	63 891	68 413	86 514	93 302
Addressed share of market (%)	75,00%	75,00%	75,00%	75,00%	75,00%	75,00%	75,00%	75,00%
Total addressed volume (units)	2 661	3 145	8 314	26 740	47 918	51 310	64 886	69 976
Total addressed volume (tonnes)	913	1 079	2 852	9 171	16 435	17 598	22 254	24 000
Total captured volume (units)	2 661	3 145	8 314	26 740	47 918	51 310	64 886	69 976
Total captured volume (tonnes)	913	1 079	2 852	9 171	16 435	17 598	22 254	24 000
Packaging units needed	41	7	79	278	316	87	203	146

Estimated flows

	2023	2024	2025	2026	2027	2028	2029	2030
Volumes addressed (units)	2 661	3 145	8 314	26 740	47 918	51 310	64 886	69 976
Number of packaging units shipped including customer acceptance and market share (units)	1 253	1 470	3 858	12 319	21 917	23 297	29 246	31 308
FTL needed if optimized	26	30	78	247	439	466	585	627
FTL needed with custom fill rate	35	40	104	330	586	622	780	836
Average number of EVBs in inbound storage	7	8	21	68	120	128	160	172
Storage needed for EVBs (sqm)	12	14	38	122	216	230	288	309
Storage needed if EVBs stacked (sqm)	4	5	13	41	72	77	96	103
Storage needed with 90% fill rate for EVBs (sqm)	14	16	42	135	240	255	321	343
Storage needed for EVBs with 90% fill rate and stacking (sqm)	5	5	14	45	80	85	107	114
Storage needed if empty containers stacked (sqm)	3	4	11	34	60	64	80	86
Storage needed for empty containers with 90% fill rate and stacking (sqm)	4	4	12	38	67	71	89	95
Yearly cost of storage space (€)	3 020 €	3 543 €	9 301 €	29 700 €	52 840 €	56 169 €	70 510 €	75 482 €
Unloading time per month given optimized FTLs (hours/month)	9	10	26	82	146	155	195	209
Unloading time per month given FTLs with custom fill rate (hours/month)	12	13	35	110	195	207	260	279
FTEs needed for unloading operations	0,07	0,08	0,22	0,69	1,22	1,29	1,63	1,74
Handling time per month (hours/month)	52	61	161	513	913	971	1 219	1 304
FTEs needed for handling operations	0,33	0,38	1,00	3,21	5,71	6,07	7,62	8,15
Total number of FTEs needed	0,40	0,47	1,22	3,89	6,93	7,36	9,24	9,89
Total number of FTEs needed (rounded up)	1	1	2	4	7	8	10	10
Yearly cost for FTEs (€)	86 400 €	86 400 €	172 800 €	345 600 €	604 800 €	691 200 €	864 000 €	864 000 €