From Manual to Robotic Disassembly: Adhesive Lid Removal in EV Battery Packs

Master's thesis in Quality and Operations Management

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Abstract

The increasing need for efficient and safe disassembly of electric vehicle (EV) batteries has made robot automation an important focus. This thesis explores solutions of a robotic end-effector for the removal of adhesive-bonded EV battery lids, with the aim of supporting future automated recycling systems. The work is based on interviews with industry professionals, literature, and patent reviews, as well as a structured design evaluation process. Key requirements identified for automation included robustness to battery design variation, safe operation near cells, and acceptable process speed. A possible concept was evaluated: a vertically mounted shoulder mill that uses a semi-destructive approach to cut along adhesive paths without risking cell damage. While no physical testing was performed, the concept was assessed using CAD models and process calculations. For the Tesla Model S lid geometry, an estimated process time of approximately 6 minutes was calculated, with a total cutting force around 560 N at a feed per tooth of 0.08 mm. These results suggest that the tool could offer similar or better performance compared to current manual methods, while also being safer and easier to automate. Future work should include experimental validation using a robotic system, focusing on cutting performance, vibration effects, and toolpath stability.

Keywords: Electric Vehicle Batteries, Robotic Disassembly, End-Effector Design, Adhesive Bond Removal, Battery Recycling, Automation

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Adrian Markanovic, Simon Toft, Gothenburg, June 2025

List of Acronyms

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

DfD	Design for Dissasembly
EoL	End-of-Life
EV	Electric veichle
EVB	Electric veichle battery
NA	Necessity to Automate
TAA	Technical Ability to Automate

Nomenclature

Below is the nomenclature of parameters and variables that have been used throughout this thesis.

Parameters

D	Tool diameter
f_z	Feed per tooth
z	Number of teeth
a_p	Depth of cut
a_e	Width of cut
n	Spindle speed
k_{cm}	Specific cutting force for material

Variables

v_c	Cutting speed
v_f	Feed rate
p_{cm}	Power requirement
$F_{c,tot}$	Total main cutting force

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1

Introduction

In this chapter, the background to the research will be presented. The research aim and limitations will also be outlined, together with the research questions that will guide the research forward.

1.1 Background

The growth of electric vehicles (EVs) brings significant environmental benefits but also new challenges that must be addressed (Beghi et al., 2023). By 2035, it's predicted there will be over 525 million EVs on the roads, resulting in one in four cars being electric (Agency, 2024). Although their effects on the environment are positive, the number of End-of-Life (EoL) lithium batteries is rapidly growing, which can cause environmental issues. (Klohs et al., 2023)

If current practice continues, close to 5,750,000 tons of retired batteries could end up lying in landfills by 2040 (Gadgil et al., 2024). When they are left in landfills, they do not just sit harmlessly. Over time the battery might degrade, leading to toxic metals and electrolyte chemicals to leak into the soil and groundwater, which can lead to issues like pollution and safety risks (Gadgil et al., 2024). This highlights the need for better recycling strategies.

To support circular EV battery (EVB) production, disassembly acts as a critical step in both recycling and remanufacturing processes (Asif et al., 2024). Disassembly allows components to be safely separated, assessed, and prepared for material recovery. Its relevance is underscored by the fact that the European automotive remanufacturing market is currently valued at 45 billion and expected to reach 90 billion by 2030 (Asif et al., 2024). Efficient disassembly is therefore not only a necessary technical step but also an economic enabler for future value creation.

Since EVBs come in many different designs without a universal standard and their lack of design for disassembly (DfD), manual disassembly remains the most common method (Tan et al., 2024). It is typically performed by workers with high-voltage training (Klohs et al., 2023). Even with protective equipment, risks like short-circuiting or cell damage exist, making the task dangerous. Additionally, manual disassembly is labor-intensive and time-consuming, impacting economic viability, especially in countries with high labor costs (Kaarlela et al., 2024).

Given these safety and economic concerns, robotic disassembly has gained academic interest in recent years. A review of publications indexed in Scopus indicates a gradual increase in research activity related electric vehicle robotic disassembly (Asif et al., 2024). While the field of robotic disassembly for EVBs remains relatively small, the upward trend in publications since 2018 suggests a growing interest and recognition of its potential role in addressing EoL battery challenges. These robotic systems usually rely on machine vision (MV) to sense the environment, robotic arms for motion, and AI for control. Despite this traction, challenges remain. (Kaarlela et al., 2024).

While robots are good at repetitive tasks in structured settings, the wide variation in EVB designs makes disassembly challenging (Kaarlela et al., 2024). EVB designs differ not only across manufacturers but also within models from the same brand. Kaarlela et al, 2024, point out that variations like welded joints and adhesive bonding introduce complications for robot systems. As a result, human–robot collaboration (HRC) is currently used in the more complex tasks that require fine motor skills and judgment. While HRC helps address the technical difficulties, safety concerns for human operators still exist (Kaarlela et al., 2024).

The first step in EVB disassembly is removing the lid, which serves as both a protective cover and part of the structural frame (Erdogan et al., 2024; Hellmuth et al., 2021). Some lids are bolted and can be removed with existing robot tools. However, other EVB lids are bonded with adhesives (Harper et al., 2023). Existing research has experimented with prospective solutions for removing adhesive-bonded lid, focusing on cutting operations (Kaarlela et al., 2024). This research aims to build on that by exploring a robot end–effector tool that can detach the adhesive–bonded lids from the EVBs.

1.2 Purpose and aim

The purpose of this thesis is to explore feasible robotic end-effector solutions for the disassembly of EVB lids, specifically those bonded with adhesives. The study focuses on the early-stage concept development of a tool that can support this critical disassembly step and contribute to more automated battery recycling in the future.

The aim is to propose one concept solution for removing adhesive-bonded lids from a variety of EVB designs. The intention is not to deliver a finished product but rather to take one step closer toward a production-ready system. To achieve this, the research is guided by the following questions.

1.3 Research Questions

- **What requirements and removal mechanisms should be considered when designing a robotic end-effector for adhesive-bonded lid removal?**
  This question explores battery lid characteristics, industry needs, and existing removal methods based on patents and current market practices to define key requirements for the end-effector.
- **What is one possible concept design for an end-effector, based on identified requirements?**

This question focuses on generating and evaluating design concepts to identify one that meets the identified requirements.

1.4 Delimitations

This study focuses on EVB lids bonded with adhesives. Thus, it does not cover EVBs that use other bonding methods. Secondly, it focuses on the end-effector that directly interacts with the EVB. Thus, it does not include other subsystems required for a complete end-effector system, such as actuators, sensors, adaptors or motors.

1.5 Collaboration

This research is conducted in collaboration with a partner organization that serves as the problem owner. They are an automation EVB disassembly facility based in Luxembourg. Their goal is to fully automate the disassembly process without human intervention. The company has developed a range of robot end-effectors to manage the different disassembly tasks. However, adhesive removal, particularly from battery lids, remains a significant bottleneck.

1.6 AI Disclaimer

During the writing of the thesis, AI tools such as ChatGPT were used to assist with language editing to improve the text clarity. AI tools were not used to generate results, analysis, or figures. All interpretations and conclusions are solely done and created by the authors.

2

Theory

This chapter presents the theoretical framework that laid the foundation for the research.

2.1 EVB Disassembly

This section outlines the structure of EVBs, the typical lid removal disassembly process, and the current limitations and opportunities related to automating these procedures.

2.1.1 EVB Structure

EVB designs generally follows a hierarchical structure: pack-modules-cells. The pack, consisting of a lid and casing, acts as a protective housing for the modules and cells (Figure 2.1). This structure is typically secured using a combination of bolts, adhesives, and welds (Chew et al., 2022). Adhesives, while providing strong bonds, create significant challenges for automated disassembly. Adhesives are often applied in inconsistent ways, leading to difficulties for the robot to detect exactly where to cut or separate the parts. They also require high force to break and often resist heat, making them difficult to remove without damage. Commonly used adhesive agents are epoxies and polyurethanes because of their thermal conductivity and mechanical stability, causing disassembly difficulties, especially for automated processes (Gerlitz et al., 2021)

Figure 2.1: Overview of an EVB pack. Image provided by the partner organization.

2.1.2 Lid Removal Process

The standard process of lid removal is shown in Figure 2.2. It includes identifying the cover, unscrewing bolts, remving the bolts, separate adhesive and lastly remove it. The process continues downstream with the removal of electronic wiring.

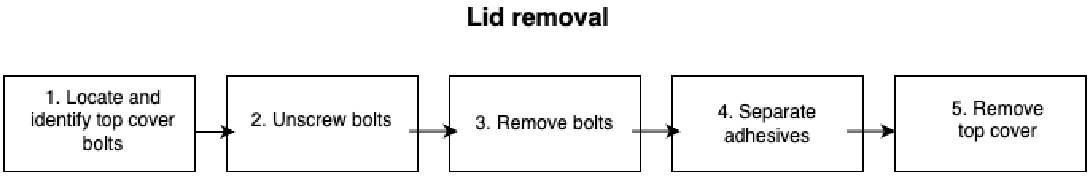


Figure 2.2: Visualization of EVB lid removal disassembly sequence. Adapted from Kaarlela et al. (2024).

2.1.3 Destructive vs non-destructive disassembly

The disassembly process can either be destructive or non-destructive (Tan et al., 2024) (Gerlitz et al., 2021). Non-destructive methods such as unscrewing aims to preserve components for reuse, while destructive methods like cutting, shearing, or milling are faster but compromise reusability because components risk getting damaged in the process. Robotic systems excel in non-destructive disassembly, as they offer precise control that minimizes damage to valuable components (Gerlitz et al., 2021). However, when robotic systems are used for non-destructive disassembly, they face challenges due to their limited flexibility. This becomes especially difficult when EVB designs vary, as precise handling and a detailed understanding of the batterys structure are required. As a result, having access to accurate and detailed information is crucial during the non-destructive disassembly method.

2.1.4 Limitations of Current Automation Efforts

While robotic disassembly is promising, a fully automated process is still considered unfeasible by most researchers due to the high variability in EVB designs (Kaarlela et al., 2024). Battery packs differ widely in geometry, joining methods, and internal layouts even among models from the same brand. This lack of standardisation, combined with limited access to design data, creates major obstacles for reliable and safe automation (Kaarlela et al., 2024; Thompson et al., 2020).

Although over 74% automation potential has been identified for recycling tasks, this is largely because destructive methods can be used, which don't require careful handling (Kaarlela et al., 2024). In contrast, remanufacturing and reuse require non-destructive disassembly, which is more difficult to automate. Many reviewed papers agree that to enable reliable robotic disassembly, batteries must be DfD (Cruz Ugalde & Talens Peiró, 2024; Gerlitz et al., 2021; Thompson et al., 2020). This includes avoiding permanent joints like welding and adhesives, and designing for tool access, for example, along a vertical axis (Kaarlela et al., 2024).

2.1.5 Automation feasibility in EVB disassembly

Hellmuth et al. (2021) investigated the robotic battery disassembly on a 2017 Chevrolet Bolt battery regarding two metrics: Technical Ability to Automate (TAA), and Necessity to Automate (NA), see Table 2.1. These show how feasible and useful it is to automate a task, which quantifies factors like danger, complexity, end-effector access, and detection feasibility.

Table 2.1: Criteria for evaluating automation feasibility and necessity. Adapted from Hellmuth et al. (2021).

Category	**Criterion Number**	**Criterion Description**
NA	1	Number of Motions (human)
	2	Duration of manual disassembly time in seconds
	3	Danger (High voltage protection, hazardous materials)
	4	Weight
	5	Priority (value)
TAA	1	Complexity of motion (for robot, number of different motions)
	2	Access for end effector
	3	Possible detection
	4	Automation potential for robotic end effector
	5	Material handling

The first step of removing the lid involves removing the bolts from the lid, which scored high on both scales. This means it is both easy and worthwhile to being automated. Robots can use standard tools like screwdrivers to remove bolts, making this step a good fit for automation. However, in some battery designs, the lid is not just held in place by bolts, it is also glued on with strong adhesives. Glued joints lack standard gripping points, which makes them difficult for robots to detect (Gerbers et al., 2018), and require careful force to avoid damaging parts (Hellmuth et al., 2021). It is perceived as one of the most challenging steps to automate due to design variability, tool access issues, and safety risks (Cruz Ugalde & Talens Peiró, 2024).

2.2 End Effector Tools

As previously mentioned, robotic disassembly systems are highly dependent on the availability of end effector tools, which are the components that directly interact with the object being disassembled, such as a battery pack (Fleischer et al., 2021). Some examples of available end effector tools for battery disassembly are illustrated in Figure 2.3. End-effector tools enable the robot to perform physical actions including handling, fastening, separating, or measuring.

In the context of EVB disassembly, commercially available end effector tools have been successfully demonstrated for tasks such as unbolting (A), cover removal (D), sorting (C), and cutting (B) (Hathaway et al., 2023).

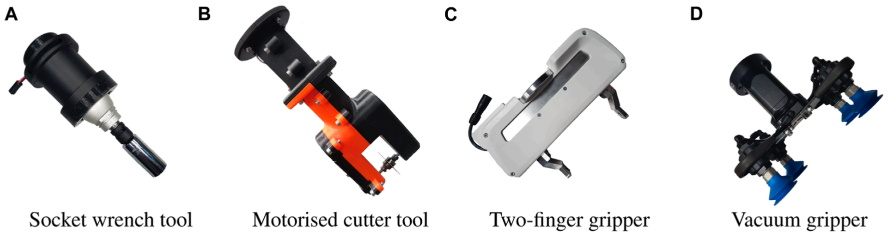


Figure 2.3: Tool attachments considered for disassembly tasks. Reproduced from Hathaway et al. (2023), distributed under the terms of the Creative Commons Attribution License (CC BY).

For adhesive joints specifically, very few practical solutions exist. One conceptual tool, a pneumatic separator was proposed to detach glued lids, but no experimental validation was reported (Kaarlela et al., 2024). Other studies mention freezing adhesives below −115°C to reduce separation force, but this method introduces new safety and handling challenges. Cutting tools have also been proposed, but cutting near battery cells risks sparks and fire, especially if gases have leaked due to thermal runaway (Kaarlela et al., 2024). Lastly, solvent-based methods release toxic fumes, increasing fire risk and complicating ventilation (Kaarlela et al., 2024).

2.3 Process Benchmarks

Hellmuth et al. (2021) conducted a case study on a 2012 Nissan Leaf battery, in which disassembly at the modular level required cutting when fasteners could not be removed using standard tools. In this case, the cutting was used to remove the module cover protecting the battery cells underneath. The task involved four linear cuts and took approximately eight minutes per module to expose the cells (Hellmuth et al., 2021).

Although the setup involved a collaborative robot guided by a human operator, and the procedure was performed at the module level, the findings provide useful insight into the time and precision requirements for cutting operations in situations where non-destructive methods are not effective. Variations in process time were mainly due to difficulties in maintaining the correct path, as the operator had difficulties with the force feedback. Despite these challenges, the success rate ranged between 70% and 80%, indicating that automation of similar tasks may be feasible, particularly where components are bonded with adhesive or lack accessible fasteners (Hellmuth et al., 2021).

While this case focused on module disassembly, the findings are relevant for pack-level operations as well. In designs where the battery lid is glued in place, cutting or other destructive methods may be necessary. These destructive methods can support access to internal components when conventional removal techniques are not sufficient.

2.4 Milling

Milling is a destructive method, typically used to shape many different types of surfaces, both flat and curved (Elshennawy & Weheba, 2015). It can be used on the outside or inside of a workpiece. In most cases, the workpiece is moved past a rotating tool called a milling cutter, which has several teeth. These teeth remove small amounts of material one after the other. There are different ways to do milling depending on what shape is needed. The method used depends on the type of machine, the cutting tool, the shape and position of the part that is supposed to be milled. Each tooth on the milling tool works like a small cutting tool. The teeth are usually placed at equal distances, but sometimes they are not. This can help reduce vibration and noise during milling.

To perform milling operations effectively, it is important to understand and control several key process parameters. Table 2.2 provides an overview of the most relevant parameters used in milling, along with their units and brief explanations.

Table 2.2: Overview of process parameters for milling

Process parameters	**Unit**	**Parameter definition**
v_c	[m/min]	Cutting speed
D	[mm]	Tool diameter
f_z	[mm/tooth]	Feed per tooth
z	-	Number of teeth
a_p	[mm]	Depth of cut
a_e	[mm]	Width of cut
n	[rpm]	Spindle speed
v_f	[mm/min]	Feed rate
k_{cm}	[N/mm^2]	Specific cutting force for material
P_{cm}	[kW]	Power requirement
$F_{c,tot}$	[N]	Total main cutting force

2.4.1 Equations for milling

In milling operations, several equations are used to describe and calculate key process parameters (Elshennawy & Weheba, 2015). These are important for planning, controlling, and analyzing the cutting conditions.

Cutting speed (v_c) is the speed at which the outer edge of the milling tool moves while the tool rotates. It tells how fast the tool is cutting through the material at its edge. The spindle speed (n) and the tool diameter (D) is needed to calculate the cutting speed. As the diameter is described in millimeters and spindle speed in rpm, it is divided with 1000 in order to obtain [m/min]. This can be rearranged to be solved for the spindle speed (n).

$$v_c = \frac{\pi \cdot D \cdot n}{1000} \implies n = \frac{1000 \cdot v_c}{\pi \cdot D} \tag{2.1}$$

The feed rate (v_f) is the distance the workpiece moves forward every minute while the milling tool is cutting. It is calculated based on the feed per tooth (f_z), the number of teeth (z) and the spindle speed (n).

$$v_f = f_z \cdot z \cdot n \tag{2.2}$$

To estimate the power requirement (p_{cm}),the equation includes the depth of cut (a_p), the width of cut (a_e), the feed rate (v_f), and the specific cutting force for the material (k_{cm}).

$$p_{cm} = \frac{a_p \cdot a_e \cdot v_f \cdot k_{cm}}{60 \cdot 10^6} \tag{2.3}$$

To estimate the cutting force (F_c), the equation includes the depth of cut (a_p), the feed per tooth (f_z), and the specific cutting force for the material (k_{cm}).

$$F_c = k_{cm} \cdot a_p \cdot f_z \implies F_{c,tot} = F_c \cdot z \tag{2.4}$$

To estimate the machining time (t_s), the equation includes the total cutting length (L) and the feed rate (v_f), where the length is divided by the feed rate to calculate how long the cutting process will take.

$$t_s = \frac{L}{f_z \cdot z \cdot n} \implies t_s = \frac{L}{v_f} \tag{2.5}$$

3

Methodology

This chapter outlines the methodological framework employed to address the two research questions, focusing on the concept design of an end-effector for detaching the adhesive-bonded lid from the EVB. A mixed-methods research approach was used, incorporating semi-structured interviews, patent review, and on-site visits together with concept evaluation and performance calcualations.

3.1 Research Design

This section explains how the research was designed to develop the end-effector tool. It describes the overall research approach and the reasoning behind it.

3.1.1 Research Approach

A mixed-methods research approach was used to guide the development of the end effector. This approach ensures that the tool's design is grounded in real-world requirements identified together with market experts. It combines qualitative methods, such as interviews, with quantitative methods, such as calculations and metrics evaluation. The mixed-method approach will follow an exploratory sequential design, as the qualitative data inform the development of the practical tool, followed by quantitative calculations to test performance(Bell et al., 2019).

3.1.2 Logic of Reasoning

Regarding the relationship between theory and research, this study employed an abductive approach. While deductive research tests existing theories and inductive research builds theories from data, abductive reasoning offers a middle ground (Wallén, 1996). It starts with empirical observations that are puzzling or unexpected that moves back and forth between data and theory to develop explanations. This logic is well-suited for guiding the study, due to its exploratory nature and limited existing research.

3.2 Research Method

An overview of the research method is presented in Figure 3.1, and the sum of data collections in Table 3.1

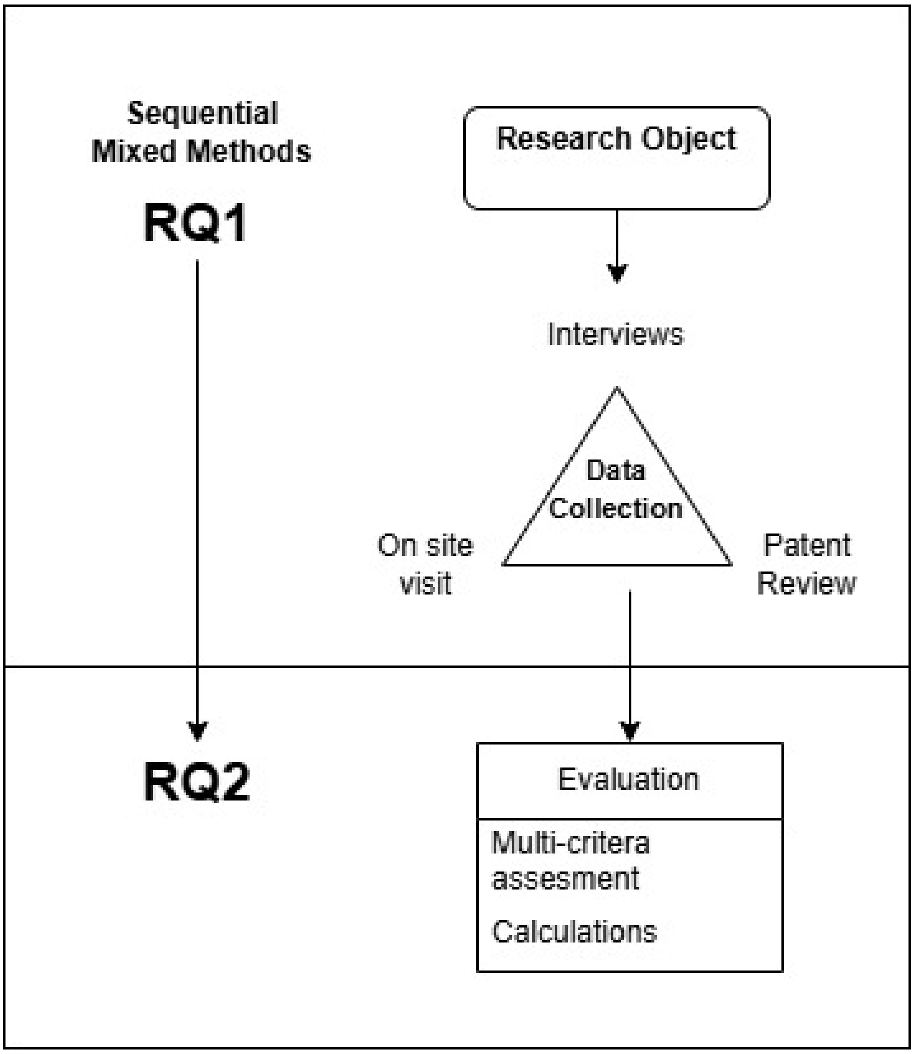


Figure 3.1: Overview of the sequential mixed methods approach used in this study.

Table 3.1: Overview of Data Collection Methods

Data Collection Method	**Number**
Interviews	8
On-site Visit	2
Patent Review	1

3.2.1 Industry Interviews

Eight semi-structured interviews were conducted with industry experts involved in EVB disassembly and automation. The aim was to understand current challenges and requirements for robotic lid removal, which directly supports RQ1.

3.2.2 Observation at Recycling and Disassembly Facility

Two on-site visits were done, one at a battery recycling facility and one at an automation disassembly facility. Field notes were collected during both visits. The purpose was to gain practical insights into the disassembly process, with a focus on lid removal, and to compare these observations with the interview findings, supporting RQ1.

3.2.3 Patent and Tool Review

A total of 34 relevant patents and existing industrial tools were reviewed. The goal was to explore available technical solutions and mechanisms for lid removal. This data collection supports both RQ1 by showing what solutions currently exist and RQ2 by informing tool design possibilities.

3.3 Data collection

This section explains how data was collected for the study. It covers the interviews, the patent screening, and the on-site visits that helped gather information.

3.3.1 Interviews

A purposive sampling approach was used at the start of the study. This is a non-probability sampling method in which participants were selected based on predefined criteria, such as their professional roles, experience with battery disassembly, and involvement in relevant industrial processes (Bell et al., 2019). A snowball sampling was used in combination with purposive sampling. Snowball sampling refers to starting with an initial contact who is known to have some relevance to the research topic, and then using their network (Bell et al., 2019) and insights as guidance to identify additional individuals who could contribute to the study (Säfsten & Gustavsson, 2024). These two sampling strategies were combined due to the limited availability of participants within the specialized field of study. This approach helped ensure early relevance and made it possible to reach more experts. This led to interviewing people who had specific knowledge and experience with EVB disassembly and related processes.

The interviews were carried out using a semi-structured format. This approach has a low level of structure, giving respondents the freedom to answer in their own way (Patel & Davidson, 2019). While a number of questions were prepared in advance, they were not asked in a fixed order. Instead, the direction of the interview was guided by the responses, allowing the conversation to develop naturally and leading to follow-up questions based on what the respondent shared.

A total of 8 interviews were conducted, see Table 3.2. Two of the interviews were held in person, where both sides had the chance to meet face-to-face. This was the second and the last interview. The other interviews were done through video calls using Microsoft Teams, as a result of not being able to meet in person. Meetings in person can be helpful, as seeing each other can create a feeling of trust between us and the respondent (Säfsten & Gustavsson, 2024). All interviews were recorded and later transcribed. Before each interview, permission was asked to record the conversation together with going through the informed consent.

Table 3.2: Overview of conducted interviews. Note: Milling experts only interviewed for concept verification

Interview ID	Role	Company Type	Date
INT01	CEO	EV Converter	2025-02-25
INT02	CEO	Battery Dissasembler	2025-02-28
INT03	Battery Test Engineer	OEM	2025-03-07
INT04	Mechanical Engineer	Dissasembly facility	2025-03-12
INT05	R&D Polymer Expert	Research Institution	2025-03-28
INT06	CEO	Recycling Facility	2025-04-02
INT07	Battery Engineer	OEM	2025-04-03
INT08	Two R&D Milling Experts	Research Institution	2025-05-07

The interviews at the beginning of the project were based on the general research made for the background on EVB disassembly. Because the literature was limited, the knowledge was built through the interviews, which gave new insights that were explored further. The patent screening also gave new information, which made the interviews look different towards the end of the thesis. No sample size was set in advance, as the topic is relatively unexplored (Kaarlela et al., 2024). Instead, interviews were carried out until no major new insights appeared, which is often referred to as thematic saturation (Guest et al., 2006).

3.3.2 Patent Screening

Meanwhile interviews were held, a total of 204 records were identified using Espacenet database searches. The search string, see Appendix A.1, returned a mix of patents and utility models, as Espacenet includes both types by default. No manual filtering was applied to differ between the two, and both were considered in the screening process. The OR operator was used to include the terms battery, lithium-ion battery, and EVB to keep the search broad. This helped in avoid limiting the results only to the EV field and allowed for further insights from more developed areas like smartphones and laptops. Before screening, 3 records were excluded due to language barriers, resulting in 201 records to be screened. During the screening, 167 records were excluded based on three criteria, see Table 3.3. This left 34 reports for review. All 34 reports were assessed in full text for eligibility. No additional reports were excluded at this stage, and no reports were retrieved from other sources. An overview of the screening process can be seen in a PRISMA flow diagram (Figure A.1 in Appendix A.1.1).

The final review included 34 patents and utility models, which were used for qualitative and quantitative analysis.

Table 3.3: Exclusion Criteria with Examples

Reason	Examples / Description
Reason 1: Irrelevant Technical Focus	Alt 1) Focus on adhesive layering rather than removal Alt 2) Bonded with adhesive tape instead of glue Alt 3) Related to other bonding mechanisms
Reason 2: Lack of Applicability	Too general or non-technical to be applied to robotic battery disassembly
Reason 3: Insufficient Information	The description lacked technical detail necessary to assess relevance (e.g., abstract only, no drawings)

3.3.3 On-site visit

Two on-site visits were conducted to collect first hand data on disassembly practices. The first visit was held at the partner organisation's battery disassembly facility in Luxembourg. The visit started with a 60-minute presentation led by a production engineer, covering the company's approach to EVB disassembly, automation goals, and current system challenges. The session included an open Q&A format, allowing questions throughout.
The second visit took place at a bigger-scale recycling facility in Sweden. Informal conversations with business specialists were combined with close observation of disassembly procedures. In total a 2-hour guided walk-through of the facility was conducted. This included live observations of the entire disassembly chain, from initial battery discharge, lid removal, and hazardous materials separation to black-mass recycling. Although not following a formal structured observation, key activities were documented using notes to capture the environment in a natural way (Bell et al., 2019). Informal discussions during the walk-around helped clarify practical considerations such as tool access, lid design issues, and safety issues relevant to adhesive-bonded joints. It should be noted that no live disassembly of the lid was observed.

3.4 Data Analysis

This section describes how the data was analyzed. It includes the interview analysis, the patent analysis, and the on-site visit analysis.

3.4.1 Interview Analysis

A thematic analysis was applied to analyze the interviews. A thematic analysis is when you look through qualitative data to find patterns, called themes, by first identifying smaller parts of the text known as codes (Bryman, 2016; Säfsten & Gustavsson, 2024). The transcripts of the interviews were read through, and certain expressions and sentences were identified. These were then written down as short codes that summarized the meaning. From these codes, patterns were searched for to see if the codes could be grouped under common themes. For instance, several codes were related to tool requirements and existing practices or solutions for the lid removal process were identified. These types of codes helped us shape the main themes, which in the end were clearly connected to requirements mentioned by the experts and solutions they had seen work well in practice. After sorting the codes into different themes, we reviewed the themes again to adjust the structure and remove anything that was not relevant to our research questions. Some codes, for example, did not form a pattern and were not synthesized further. One such case was one interviewee mentioned, “We use an electronic hook attached to the sealing to help lift batteries”. At first, this was seen as a potential code, but after comparing it with other data, we saw that it did not link to any clear pattern or category. It mainly described a tool used for general handling of battery waste, which fell outside the scope of the analysis.

3.4.2 Patent Analysis

To analyze the remaining patents, a qualitative approach based on a thematic synthesis was done, similar to the interview analysis. It works well for going from a lot of raw text, like patents, to finally conceptualized themes. In this instance, the themes will be conceptualized as mechanism concepts, acting as potential solutions to the end-effector tool.

The synthesis started with all eligible patents and utility models, with their rubric, abstract, texts, and images merged into a single document. The initial coding was performed directly from the patent wording, with relevant keywords highlighted using color-coded markers. These initial codes were taken, with their exact phrases directly from the patents to keep the technical context.

Next, similar codes were grouped into broader themes that captured common approaches or ideas. For instance, codes like “rotating blades” or “mechanical edge contact” were grouped under the theme “Scraper” while other codes, including “thermal application” and “flame device,” were grouped into “thermal”. Lastly, the synthesized themes of potential mechanisms were inputed into the concept evaluation process.

3.4.3 On-site visit analysis

The analysis of the on-site visits was done by reviewing field notes and observations collected during the facility walk-throughs. These were compared against themes from the interview data to identify similarities and differences. Key points were grouped into categories related to tool access, safety, process time, and handling of adhesive joints. The purpose was to better understand real-world disassembly practices and to support the development of tool requirements. The observations were also used to cross-check and validate insights from interviews and the patent review.

3.5 Research Quality

To ensure research quality, several strategies were used. First, triangulation was applied by combining interviews, on-site observations, and patent reviews. This helped reduce bias and improved the credibility of the findings.

Even though generalisability is limited due to the wide variety of EVBs and no real-world testing, the results are reliable within the scope of this study. A validation workshop was also held at a battery research center. While no new data was collected there, experts gave feedback that confirmed the studys findings. In addition, professors from Chalmers University of Technology, with backgrounds in mechanical, industrial, and materials engineering, provided guidance, especially related to tools and robotics. Finally, regular check-ins with industry partner helped ensure that the research stayed relevant to real-world applications.

3.6 Ethical Considerations

Throughout the study, key ethical principles were followed to protect participants and ensure responsible research practice. All interviewees were clearly informed about the purpose of the study and gave their consent to participate. Personal and organizational details were anonymized, and care was taken to remove any information that could indirectly reveal someone's identity, especially given the small sample size. Sensitive material that could affect the partner company's intellectual property or competitive position was excluded from the thesis. Lastly, no participants were misled about the aim of the research or how their input would be used, helping maintain transparency and trust throughout the process.

3.7 Concept Evaluation Method

Based on requirements and mechanisms identified, a set of alternative concepts were generated. These were evaluated using a weighted matrix based on factors like robustness, safety, and process time. A Tesla Model 3 CAD mockup was illustrated in computer-aided desing (CAD) to test layout and tool reachability.

The final concept was evaluated using basic performance calculations to check its suitability for real applications. These included force calculations and time calculations for the lid removal process.

3.8 Evaluation proccess

The concepts generated were evaluated using a process described by Ulrich and Eppinger (2014). The process can be explained through three matrices used to arrive at the final concept:

1. Concepts that do not meet the criteria in the requirement specification are removed, using the Elimination matrix.
2. A concept screening is carried out using the Pugh matrix, a relative decision-making matrix.
3. The different criterions from the requirement specification are weighted against each other, and the remaining concepts are scored to select the final concept, using the Kesselring matrix.

3.8.1 Elimination matrix

All concepts developed through the process were evaluated using an Elimination matrix. In the elimination matrix, all the requirements from the requirement specification and all the concepts were listed. If a concept was considered to meet a requirement, a ’+’ was assigned. If a concept was difficult to assess and more information was needed to decide whether it met a requirement, a ’?’ was used. If a concept did not meet a requirement, a ’-’ was assigned. Any concept that had at least one ’-’ was eliminated from the matrix and did not proceed to the Pugh matrix. All concepts that remained after the screening in the elimination matrix were presented with a figure.

3.8.2 Pugh matrix

The requirements from the requirement specification were added to the matrix. The concepts that passed through the elimination matrix were then included, each with their reference letter. In the first iteration, Concept A was used as the reference for comparison. Each concept in the Pugh matrix was then compared to the reference concept using the criteria. It was judged whether each concept was better than, the same as, or worse than the reference. A ’+’ was given if the concept was better, a 0 if it was the same, and a ’-’ if it was worse. The results of these comparisons (+, 0, or ’-’) were entered into the corresponding cells of the matrix. This gave a net score for each concept, which was then used to rank them.

To make sure the results were reliable, a convergent result was needed. The concept that ranked best in each iteration was used as the new reference in the following round. This process continued until a convergent result was reached. In total, three iterations of the Pugh matrix were carried out.

3.8.3 Kesselring matrix

A weighting of the requirements defined in the requirement specification was carried out, where all requirements were compared against one another. This was done to rank the relative importance of each requirement. When two requirements were compared, their total score added up to 1. If one requirement was considered more important than the other, it was assigned a value of 1. If it was considered less important, it received a 0. If both requirements were considered equally important, each was assigned a 0.5. The values from each comparison were summed for every requirement and then divided by the total sum to obtain the average weight for each one. These weight factors were listed in the w-column of the Kesselring matrix.

To compare the concepts that remained for evaluation in the Kesselring matrix, each concept was assessed on how well it fulfilled each requirement. The requirements were rated on a scale from 1 to 5, where a score of 1 indicated that the concept performed very poorly on the requirement, and a score of 5 indicated very strong performance. The values used in the quantification of the requirements are estimated values, based on input provided by the respondents. This scoring was done within the Kesselring matrix, with each rank for the concept rated in the v-column. The scores were then multiplied by the weight factor (w) to produce the t-value, representing how well the concept met the requirement while also considering its importance. All t-values for a given concept were then summed to calculate its total merit value, T. An ideal solution was included in the matrix, receiving the highest score on all criteria, resulting in the highest possible merit value, $T - ideal$. The normalized total value for each concept was then calculated as the ratio $T/T - ideal$. All concepts were then ranked based on their highest obtained normalized merit value.

3.9 Perfomance verification

The final end-effector concept that remained after the evaluation process was verified through performance calculations and force feedback. The purpose was to ensure that the selected robot could handle the full process and that the final tool was optimized for its best performance. To support this, an on-site interview was conducted with experts in the field of milling, who provided guidance throughout the process. The values used were based on the experts recommendations to ensure an optimal process.

4

Results

This chapter presents the results of the research, including the identified requirements for the end-effector, potential mechanisms from patent review and the evaluation process, and evaluation outcomes. Each section highlights the main findings and connects them to the overall goal of designing a robotic end-effector for adhesive-bonded lid removal in EVB disassembly.

4.1 Requirements

Below are the key requirements identified through interviews with industry professionals. These requirements were later used to guide the concept evaluation process. Aggregated interview findings and how they translate into specific requirements are summarized in Table 4.1.

Robustness

The end–effector tool must be capable of removing lids from a wide variety of battery packs under different conditions. This requirement was highlighted in **6 out of 7 interviews**. Recycling facilities have no control over which battery types they receive, meaning they must handle whatever EVB that arrives. As one technician explained:

> *"We receive all types of different EVBs, and we can not decide what to disassemble and what not to."* (INT6)

Variation exists in many forms, including lid thickness and the curvature or stiffness of the packs. One disassembler described

> *"The packs are super curvy, and we had a lot of edges, thats really challenging."* (INT8)

Another shared an experience with the Tesla Model S battery:

> *"The lid was so thin, when we removed it, it looked like a metal ball."*

The adhesive used also varies. While polyurethane is common, its properties can change based on additives, as a polymer expert noted:

> *"Its polyurethane, but its very different depending on what additives they put in."*

One OEM confirmed that future battery packs will continue to use mixed joining methods:

> *"Joining methods will continue to be used in future battery packs: including screws, bolts, welds, and adhesive joints. It would be beneficial if automated methods could handle different types, even damaged packs in some cases."*

Process Time

All three recycling facilities interviewed stated that lid removal is currently performed manually. In one case, it took two hours and five workers to remove the lid from a Tesla Model S:

> *"It took us once 2 hours with 5 men, that is not feasible."* (INT4)

Spending two hours on a single lid is not economically feasible, especially at scale. If some level of destruction can reduce the time significantly, it is often considered acceptable. As INT4 continued:

> *"If the task takes 20 minutes instead, we would prefer that route. It is ultimately a balance between speed, cost, and whether component reuse is needed."*

The CEO of another recycling facility also highlighted the need for efficiency, while acknowledging that their current operation are still far from being automated:

> *"Today we are 4 to 6 workers on one EVB. Of course, it would do a lot if we could speed this process up, but we are not there yet."* (INT6)

Safety

Battery disassembly involves significant safety risks a concern raised in **7 out of 7 interviews**. One interviewee emphasized the importance of following manufacturer instructions:

> *"This is very dangerous, we never start disassembly before we retrieve guidelines from OEMs."*

In one case, a technician used an angle grinder to open a battery pack:

> *"The grinder touched the modules and went through the cells. It started to burn."*

That same technician also described a chemical leak:

> *"It started to leak out electrolytes as well. That was not good."*

These incidents highlight the need for a tool that can keep a safe distance from sensitive components and reduce the risk of damage during disassembly.

Destruction vs. Non-Destructive

All interviewees involved in disassembly discussed the trade-off between removing the lid cleanly versus using destructive methods. One automation facility summarized the decision-making well:

> *"Non-destructive is always the ambition initially but if the effort is three times higher, we go for destructive."*

A battery reseller expressed a more practical approach:

> *"The lid I usually throw away, the simplest way."*

An EV conversion company shared a similar perspective:

> *"We just want to open the pack the fastest way. If it gets damaged, that is fine, we reuse the modules, not the lid."*

While clean removal is generally preferred, destructive methods are accepted when they save significant time or cost.

4.1.1 Summary of Requirement Support

Table 4.1: Interview support across key requirement areas

Requirement	Theme Strength	Comment
Robustness	6 of 7 interviews	Strong pattern; wide design variation is expected
Process Time	All 3 recycling facilities	Manual removal is too slow and resource-intensive
Safety	7 of 7 interviews	Fire, chemical and voltage risks commonly noted
Destruction Flexibility	All disassembly-related roles	All acknowledge trade-off between time and preservation

A complete requirement specification was created based on the requirements gathered from the interviews. See Appendix A.2 for the full specification.

4.2 Mechanisms - Patent Review

This study analyzed 34 patents related to adhesive removal for EVB disassembly. Each patent was classified based on its primary mechanism for detaching bonded components. The patents included a variety of techniques and represent innovations aimed at improving battery disassembly linked to adhesive removal. The patents fall into five major mechanism categories, see Table 4.2.

Table 4.2: Mechanism categorization of patents related to battery disassembly for adhesive removal

Mechanism Type	No. of Patents	Percent	Key Features	Example Patents
Mechanical	25	73%	Drills, cutters, scraping tools	CN211100337U, CN111928318A
Chemical	3	9%	NMP, ethanol, mix of solvents	CN211100337U, CN110982716A
Laser	2	6%	Laser, precision cuts	WO2023155188A, CN217512456U
Thermal	1	3%	Induction heating	CN115511374A
Mixed/Hybrid	3	9%	Alcohol with scraper, air jet with disc cutter	CN118263555A, CN217114323U, CN118403711A

4.3 Mechanism Insights

This section presents insights from the patents, highlighting the different mechanisms and methods identified.

4.3.1 Mechanical methods

Mechanical methods remain the most patented approach for the removal of adhesive bonding. These include tools that physically pry apart glued joints. For example, Patent CN211100337U (see Figure 4.1) describes a drill rod attached to a fixed cylindrical structure. The structural part rotates as its teeth remove the glue. It has a removal hole (4) that allows for the adhesive debris to vanish through during operation. It claims to increase efficiency, saving operation time and effort while not damaging any components. Other patents in this group (e.g., CN119627266A) showcase cutting with a lead screw or cutting disc together with a feeding device that moves the cutting tool around the pack. These mechanisms vary depending on how they apply force. Drill-based tools or rotary brushes approach the bonding vertically, pushing into the glue to break it from above. Others, such as scrapers and cutting discs, work laterally by sliding along the adhesive layer to peel it apart.

CN211100337U: Drill rod (1) with teeths (5) that peels the adhesive-bonding off, allowing for the debris to fly through holes (4)

CN119627266A: C-shaped block (9) to grip lid section and screws (10) to peel the adhesive-bonding latterly

Figure 4.1: Two examples of reviewed mechanical patents

4.3.2 Chemical methods

Chemical methods offer an alternative to mechanical force by weakening the adhesive at a molecular level. These patents, which represent 3% of the reviewed patents, introduce solvent-based techniques to soften, swell, or partially dissolve adhesive joints. Instead of relying on force to break bonds, chemical methods degrade the adhesive bonding, enabling easier disassembly.

A common approach involves soaking the bonded area in solvents like N-methylpyrrolidone (NMP) or dimethylformamide (DMF), which swell the adhesive layer and reduce its grip on surfaces. For instance, patent CN118970262A applies a mixture of these solvents using an infiltration method to loosen structural glue on blade batteries. This is illustrated in Figure 4.2. It avoids high temperatures and mechanical stress, while also preserving sensitive components.

Chemical techniques are particularly valuable when material preservation is crucial. They also eliminate fire hazards caused by mechanical sparks and are compatible with automation via targeted injection or spraying systems. However, process time and the chemical compatibility with battery components remain important design considerations.

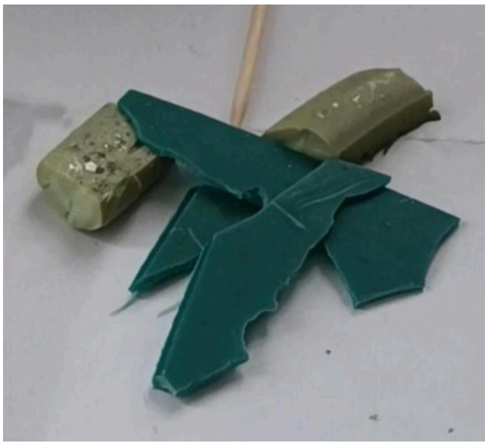


Figure 4.2: Illustration of adhesive swelling and fragmentation after solvent treatment.

4.3.3 Laser-Based methods

Laser-based methods account for about 6% of adhesive removal patents. They offer a precise, contact-free way to weaken and remove cured adhesives, which is helpful for reaching tight areas and avoiding damage. One example (WO2023115818A1) uses a pulsed laser to reduce the strength of the adhesive, making it easier to peel off using tape. This method avoids damaging the battery surface and is well suited for automation. Another patent (CN217512456U) uses two lasers, one to cut the adhesive and another to clean up any leftover material. The system combines motion control, cameras, and dust removal to keep the process smooth and accurate, as shown in Figure 4.3.

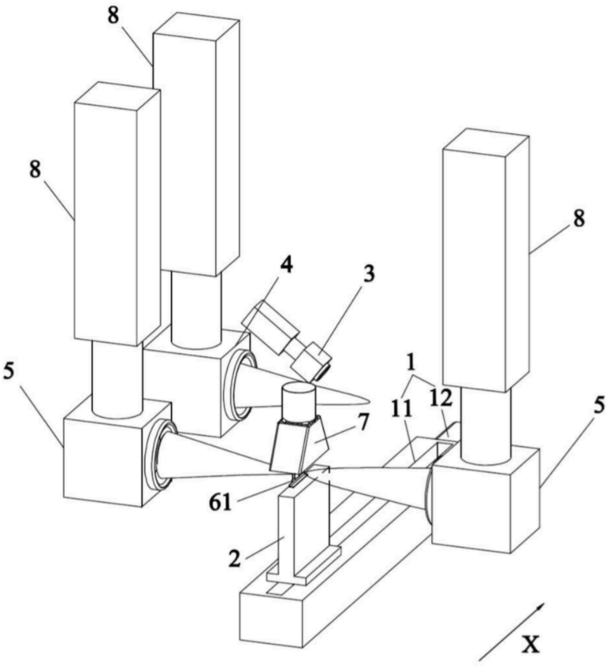


Figure 4.3: Example of a laser-assisted disassembly device. Adhesive on battery tabs is first cut using a high-precision laser (4), then cleaned via a secondary CO_2 laser module (5). The system includes motion control, vision sensing, and dust removal (CN217512456U).

4.3.4 Thermal methods

One patent was found that uses heating to remove adhesive (CN115275414A). It uses an electric thermal fuse device to create high temperatures that break down the adhesive, followed by a purification method to absorb any harmful gases.

4.3.5 Hybrid methods

Hybrid adhesive removal systems typically include a mechanical scraper, cutter, or drill, but first use heat or chemicals to soften the adhesive for easier detachment. One example (CN118263555A) integrates warm water soaking (50–60 °C) to soften polyurethane glue, followed by a mechanical scraping blade to fully remove adhesive from cell surfaces and edges. Another patent (CN217114323U) features a handheld scraper cone with an internal alcohol injection mechanism. When pressure is applied, alcohol is delivered between the glue and substrate to weaken the bond before mechanical removal. The patent claims that this dual-mechanism method minimizes operator contact with chemicals and therefore improves safety. The latter example is illustrated in Figure 4.4.

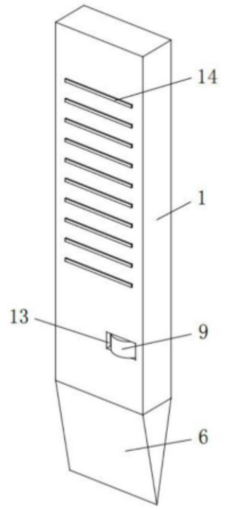


Figure 4.4: Glue remover scraper (CN217114323U). The main body (1) stores alcohol in a chamber (9), which is pushed out through an outlet (13) when the user applies force. The scraper tip (6) slides between surfaces to help peel glue, while slots (14) release pressure.

4.4 Interview Findings on Adhesive Removal Practices

In addition to the patent review, several interviews were conducted to understand how professionals currently deal with adhesive-bonded battery lids. The answers show a mix of manual, experimental, and practical approaches, see Table 4.3 for a summary of mechanism types and tools mentioned. The following quotes represent insights from interview participants across different parts of the battery disassembly industry

One dismantler, who has manually opened over 80 EVBs, uses an angle grinder with a toothed blade disc. The tool is inserted laterally under the lid to cut through the adhesive:

"A violent but effective method, that gets the job done."

A researcher at a battery facility described early-stage experiments with automated adhesive removal using end milling, combined with AI-based screw detection. They acknowledged that:

"The glue and screws are often co-bonded."

While stated as promising in experimentations, the method is not yet production-ready, and of destructive methods, it slices laterally both the bolts and adhesive bonding simultaneously.

"It cuts through bolts as well."

An EV conversion company CEO, working mostly with Nissan Leaf packs, uses a multi-tool fitted with a thin cutter. He noted that this method is:

"Recommended by the OEMs disassembly manual."

It generally works, but friction can heat up the blade and cause the glue to re-harden:

"Sometimes I have to go back to the same spot because it is stuck again."

Two recycling facilities said they rely mainly on manual labor. Crowbars and multi-tools

are their go-to tools. One facility had tried a chemical method discovered by an in-house researcher, but dropped the project due to high costs and low robustness.
A third facility reported strictly following OEM disassembly guidelines and avoiding any deviation:

> *"It is very dangerous. We always use OEM tools and follow instructions exactly."*

Table 4.3: Categorization of interviewees adhesive removal approaches linked to mechanism types and tools used.

Mechanism Type	**Mentions**	**Tool/Method**	**Interview ID(s)**
Mechanical	6	Angle grinder, crowbar, multi-tool, end mill, shoulder mill	INT01, INT02, INT03, INT04, INT05, INT06, INT07
Chemical	2	Lab-found solvent	INT04, INT05
Laser	0	–	–
Thermal	1	Freezing suggested	INT05
Mixed/Hybrid	0	–	–

4.5 Evaluation process

This section begins with an overview of all the concepts that were considered in the evaluation. It then presents the results from the matrices used to identify the final concept.

4.5.1 Concepts

The concepts developed from interviews and patent research are presented in Table 4.4. In total, twelve concepts were generated and taken into the evaluation process to identify the final concept.

Table 4.4: Concepts A–L.

A	**B**	**C**	**D**
Angle grinder	Heated scraper	FIN-Blade	Crowbar
E	**F**	**G**	**H**
NMP + Scraper	Alcohol + Scraper	Saw	Laser
I	**J**	**K**	**L**
60°C H_2O + Scraper	Freeze + Scraper	End-mill	Shoulder-mill

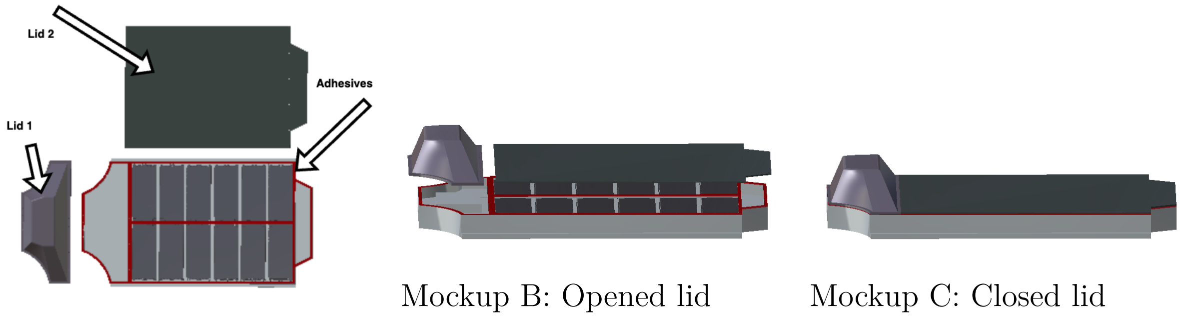
4.5.2 Battery design

The concepts generated were based on the identified requirements and common lid-adhesive bonding designs observed in EVBs. To support the evaluation, dimensional data was collected from in-house measurements at the partner disassembly facility, triangulated with interviews and public data. These approximated measurements provided realistic constraints for the parameters, which were used to assess each concepts feasibility. See table 4.5 for approximate dimensions.

Table 4.5: Approximate dimensions of EVBs.

Measurement Parameter	Minimum	Maximum	Average
Adhesive bond width	5 mm	21 mm	11 mm
Lid thickness	2 mm	7 mm	4.5 mm
Length of lid 2 for EVB	1000 mm	1960 mm	-
Width of lid 2 for EVB	1000 mm	1430 mm	-

To complement the data, a set of CAD mockups was created based on the Tesla Model S pack. These mockups helped visualize lid geometry and adhesive placement, and served as reference objects when evaluating tool access and cutting paths, see Figure 4.5.



Mockup B: Opened lid

Mockup C: Closed lid

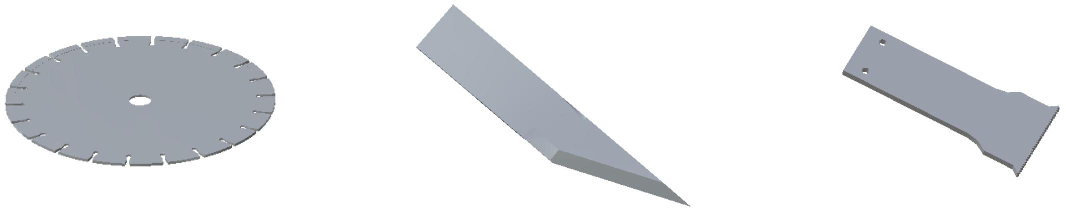
Mockup A: Schematic overview

Figure 4.5: CAD mockup of a Tesla Model S battery pack. The models illustrate lid form, adhesive placement, and pack geometry based on in-house measurements and publicly available teardown references.

4.5.3 Elimination matrix

The twelve concepts, labeled A to L, were evaluated using the Elimination matrix. Three of the concepts were removed because they did not meet the robustness criteria. It was not possible to confirm the type of polyurethane used in different battery modules, which made these solutions unreliable. Another three concepts were eliminated due to safety concerns, as they posed a risk of damaging the modules, potentially leading to a fire. One concept was excluded because it did not meet the requirement for process time. The complete Elimination matrix can be found in Appendix A.3.

The remaining concepts are shown in Figure 4.6. These concepts were carried forward to the Pugh matrix for further screening.



Alt A: Angle grinder Alt B: Heated Scraper Alt C: FIN-blade

Alt K: End-Mill Alt L: Shoulder-Mill

Figure 4.6: Remaining concepts after the elimination matrix.

4.5.4 Pugh matrix

Concept A was used as the reference in the first iteration of the Pugh matrix, where Concept L received the highest ranking and Concept B the lowest. In the second iteration, Concept L was set as the new reference. This time, Concept C ranked highest, while Concept A ranked lowest. For the third iteration, Concept C was used as the reference, with Concept L performing best and Concept B performing worst. A convergent result was achieved, and Concept B was eliminated as it consistently received the lowest rankings. A summary of the rankings from the Pugh matrix can be seen in Table 4.6. The complete iterations of the Pugh matrix can be seen in appendix A.4.The four remaining concepts were further evaluated using the Kesselring matrix.

Table 4.6: Ranking from Pugh matrix.

	Rank concept				
Concept	A	B	C	K	L
	First iteration				
Rank	R	4	3	2	1
	Second iteration				
Rank	3	2	1	2	R
	Third iteration				
Rank	2	3	R	2	1

4.5.5 Kesselring matrix

The weighting of the requirements is presented in Table 4.7. As shown, safety received the highest weighting of 0.50, while Destruction received the lowest weighting of 0.083.

Table 4.7: Weight for Kesselring matrix

Kesselring matrix - Weight							
Requirements		A	B	C	D	Sum	Weight
A	Robustness	x	0.5	0	1	1.5	0.25
B	Process time	0.5	x	0	0.5	1	0.17
C	Safety	1	1	x	1	3	0.50
D	Destruction	0	0.5	0	x	0.5	0.08

The quantification of the requirements is based on the interviews, where values have been estimated using a scale from 1 to 5. Note that criteria 3.1 to 3.3 have been interpreted as the risk of a fire occurring, as this could potentially be a direct consequence if the criteria are not met. Criterion 3.4 could not be measured and is therefore excluded from the weighting. The quantified scale of the requirements is presented in Appendix A.5.

The results from the Kesselring matrix are presented in Table 4.8. The final concept, Concept L, was determined based on its performance in relation to the weighted requirements, with a total weighted score of 0.87. The final concept that is a shoulder mill will now be verified in the next performance verification. The complete Kesselring matrix can be seen in Appendix A.6.

Table 4.8: Result Kesselring matrix

	Ideal	**Concept A**	**Concept C**	**Concept K**	**Concept L**
T (Total weighted value)	5.00	3.25	3.58	3.42	4.33
T / T_{ideal}	1.00	0.65	0.72	0.68	0.87
Rank	-	4	2	3	1

4.6 Performance verification

To verify the concept and its feasability, useful insights from the milling experts were gathered and adressed. The insights are presented in the following section, focusing on the final tool concept, the shoulder mill.

The interview centered on the design of the milling tool, particularly its diameter, tool cutting length, and number of teeth. When milling aluminum, especially certain alloys, the material can become sticky, causing it to stick to the tool and reduce precision. To address this, tools with fewer teeth were recommended to increase spacing between teeth and reduce adhesion. Regarding the diameter of the mill, the cutting width (a_e) should be around 70 percent of the actual tool diameter, according to the experts. Similarly, the actual cutting depth of the material should be around 60 percent of the tools cutting length to have a safe margin.

Furthemore, high cutting speed (v_c) was pointed out as critical, with 8000 rpm (n) suggested to ensure efficient performance when milling aluminium. In terms of feed per tooth (f_z), it was recommended to start with a low value of 0.08 mm/tooth. This allows for an initial assessment of tool behaviour, with the possibility to gradually increase the feed in small increments based on performance. The experts said that the aluminum lids of the batteries can vary a lot. Therefore, a general value was used. However, it is preferred to know the exact type of aluminum, for example, whether it is an alloy or pure aluminum. For force estimation, a specific cutting force (k_{cm}) of 500 N/mm^2 was recommended, applicable for aluminium in general. The recommended parameters for the milling process, based on expert input, are summarized in Table 4.9.

Table 4.9: Expert recommendations for milling parameters

Parameter	**Recommendation**	**Notes**
Number of teeth (z)	2 teeth	Reduces material accumulation due to bigger spacing between teeth
Tool diameter (D)	30 mm	Cutting width should be approximately 70% of the tool diameter
Tool cutting length	12 mm	Cutting depth should be approximately 60% of the tool's cutting length
Spindle speed (n)	8000 rpm	Suggested to achieve high cutting speed when milling aluminium
Feed per tooth (f_z)	Start at 0.08 mm/tooth	Begin with a lower value to observe tool performance, then increase
Specific cutting force (k_{cm})	500 N/mm^2	General value for aluminium/aluminium alloys

4.6.1 Verification of calculations

The adhesive bond width, which had a maximum of 21 mm, defines the maximum cutting width. As a result, a_e is set to 21 mm. The maximum lid thickness is 7 mm and corresponds to the cutting depth, a_p. The length used to calculate the machining time was based on the approximate maximum rectangular area of Lid 2, measuring 1960 x 1430 mm. The total time calculations were based on the Tesla Model S battery pack for Lid 2. Table 4.10 presents the calculated values for cutting power, total cutting force, and machining time for three different feed per tooth values. As f_z increased from 0.08 mm/tooth to 0.12 mm/tooth, the feed rate v_f increased from 1280 mm/min to 1920 mm/min, while the cutting speed v_c remained constant at 754 m/min. This resulted in a corresponding increase in specific cutting power p_{cm} from 1.568 kW to 2.352 kW, and total cutting force $F_{c,tot}$ from 560 N to 840 N. The total machining time t_s decreased with increasing f_z from 6.8281 minutes to 4.5521 minutes.

Table 4.10: Result calculations

f_z [mm/tooth]	v_c [m/min]	v_f [mm/min]	p_{cm} [kW]	$F_{c,tot}$ [N]	t_s [min]
0.08	754	1280	1.568	560	6.8281
0.10	754	1600	1.960	700	5.4625
0.12	754	1920	2.352	840	4.5521

5

Discussion

This chapter begins by linking the findings back to the initial research objectives and then discusses how they connect to and build upon the current theoretical landscape. It is also followed by reflections on societal, ethical, and sustainability aspects. Lastly, recommendations for how future research could support or build upon this thesis are presented.

5.1 Linking Back to the Research Objectives

The purpose of this thesis was to explore feasible robotic end–effector solutions for removing EVB lids bonded with adhesive. The aim was to propose one concept based on technical and practical requirements that could support safer and more efficient battery disassembly.

The work was guided by two research questions. The first focused on what requirements and mechanisms should be considered when designing a robotic end–effector. This was answered through a combination of interviews, patents, and on-site visits. The findings showed that robustness, process speed, and safe operation near battery cells were key requirements and that semi-destructive methods can be acceptable when lid reuse is not needed. Mechanical mechanisms were also the most common approach in both current practices and in the patent review, strengthening the case that mechanical solutions should be considered and evaluated further.

The second research question aimed to define a possible concept design. Based on the identified requirements, a shoulder mill arrived as the final concept. Although it was not physically tested, it was evaluated using performance calculations and expert feedback. The shoulder mill seems promising, especially in terms of safety and speed compared to current practices. Calculations based on tool diameter, feed rate, and total cut length suggest that the shoulder mill could achieve better process times, reducing a two-hour manual process time down to 6 minutes. From a safety perspective, the tool only cuts above the adhesive–path, avoiding slicing the battery cells laterally. This reduces the risk of short circuits or accidental damage. Overall, the work contributes with a concept that fits both within industry needs and theoretical frameworks like TAA/NA, which will be further discussed in the next section.

5.2 Theoretical Implications

To better understand the broader relevance of the findings, this section reflects on how the results align with and contribute to existing theoretical frameworks.

5.2.1 Automation feasability

To reflect on the end–effector concept and its automation potential for adhesive-bonded lid removal, the TAA/NA model from Hellmuth et al. (2021) was used. Based on interviews and observations, the step scores high in NA. Today, its only removed manually, takes a lot of time, and has occasionally led to safety issues or even cell damage, which highlights the need for automation. From a TAA perspective, tool access is limited since the adhesive is hidden under the lid. However, as the tool cuts through the lid and adhesive, the tool access is not a constraint. Furthermore, the adhesive and screws are usually aligned vertically, which means that the adhesive path can be estimated by locating the screws. This makes detection feasible with existing technologies. Since no other movements are required beyond following the adhesive line, the concept fits well with the TAA/NA model and could be a solid candidate for enabling automation.

5.2.2 Trade-offs in Disassembly

The final concept uses a semi-destructive method to detach the battery lid. This might seem like a contradiction to the non-destructive disassembly principles often described in theory, where the focus is on preserving parts for reuse. However, the findings suggest that trade-offs are necessary in real situations. In this case, the lid is considered a low-value component, especially when the battery is going to recycling. This supports the idea that in some cases, a controlled destructive approach can be more realistic than trying to preserve every component.

5.2.3 Variation in EVBs

A common challenge in battery disassembly is the variation between pack designs. Different OEMs use different materials, lid shapes, and adhesive types. This can be one reason why findings supported a mechanical approach rather than, for instance, a chemical approach. As the adhesive was bonded in the middle section in the Tesla Model S, the semi-destructive method was necessary to make it robust for this instance, as tool access would not be possible otherwise. Lastly, some adjustments were made after the expert feedback, such as reducing the number of cutting teeth to avoid material build-up inside the end–effector. This was also to make sure the tool can handle debris from all types of different adhesive formulas and lid aluminum.

5.3 Societal, Ethical, and Sustainability Reflections

The focus of this thesis has been on end–effector development to remove EVB lids bonded with adhesive. Although its nature is technical, it is important to reflect on some of the broader implications, focusing on societal, ethical, and sustainability aspects.

For example, introducing a new technology that increases efficiency in a big industry like EVB recycling can have a societal effect. Moving from a human–centric process to robots doing the work might lead to layoffs and increased stress on individuals due to the loss of stable income. However, as new technologies arise with new processes and routines, new skills and roles rises in demand. Therefore, company owners and leaders need to take responsibility to educate its workers to meet those new demands, opening up possibilities for job transitions rather than layoffs.

From an ethical perspective, it is also important to acknowledge if any specific or homogeneous group benefits disproportionately from a more automated recycling process. It might be that workers with higher education, or with pre-existing skills in this area, gain advantages, leaving other groups with less domain-specific knowledge at a disadvantage. Once more, the need for in-house education from organisations leading the change should be considered to ensure inclusivity.

Lastly, sustainability is relevant to consider, both in terms of environmental impact but also economic and societal aspects. The background leading up to this thesis covered some sustainability problems, focusing on all three pillars. By moving to a more automated process without human intervention, worker safety issues can be reduced. Environmental issues may also be addressed, as automated processes can better keep up with the increasing number of EVBs reaching EOL, ultimately mitigating risks of metals and toxins degrading into groundwaters.

5.4 Methodological Reflections

The work combined qualitative interviews, patent reviews, and on-site visits. These methods helped gather insights from both industry practice and existing technical solutions. The findings were then used in an evaluation process to arrive at a final concept design. This concept was verified through quantitative calculations and reviewed by experts in milling and automation. Their feedback added reliability to the findings by confirming the robustness of the evaluation and supporting the overall direction. Together, this offered a form of triangulation between different sources.

However, no physical testing or integration work was carried out. The design was not tested in a real disassembly environment or with real battery packs. This limits how much can be concluded about how the tool would perform in a real-life disassembly settings. Future work could focus on testing the concept in real setups and exploring how it fits into the larger system. The recommendation would be to conduct a desing of experiment.

5.5 Recommendations

A Design of Experiments (DOE) setup is recommended to investigate the influence of key variables:

- **Number of cutting teeth:** 2, 3, 4, 5
- **Feed rate:** 0.08, 0.12, 0.16 mm/rev

These will be treated as independent variables. Outcomes like cutting force, vibration levels, and toolpath accuracy can be used as dependent variables.

One potential challenge is that some robot systems include vision sensors mounted directly on the robot arm. Excessive vibration especially from high feed rates or a high number of cutting teeth could interfere with these systems, causing tool path deviation or errors in lid removal.

This highlights the need to study interactions between selected parameters, as they may have confounding effects. A structured DOE approach would help identify robust and safe design parameters for real-world operation.

6

Conclusion

This thesis set out to explore robotic end-effector solutions for removing adhesive-bonded EV battery lids. Based on interviews, patent analysis, and real-world observations, key requirements and existing methods were identified.

A concept was presented as one possible solution based on requirements: a vertically mounted shoulder mill designed to follow a fixed cutting path through adhesive without interfering with battery cells. While the end effector uses a semi-destructive approach, this trade-off was found to be acceptable in most recycling contexts, where lid reuse is not a priority.

No physical testing was performed, but the concept was evaluated using CAD, force and time calculations, and a established design evaluation process. Results suggest that the the end-effector could outperform existing manual methods, with higher automation potential. However, real-world validations are needed.

Future work should focus on full-scale experiments using robotic setups and further validation of process parameters such as feed rate, cutting force, and vibration control. With additional testing, the concept can be refined into a more production-ready system and contribute to safer, more efficient battery disassembly.

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A

Appendix

A.1 Patent Search String

The following search string was used to identify relevant patents from the database:

```
(ti = "Battery" OR ti = "lithium ion battery" OR ti = "ev battery") AND
(ntxt = "adhesive" OR ntxt = "glue") AND
(ntxt = "removing" OR ntxt = "removal" OR ntxt = "breaking") AND
(ntxt = "device" OR ntxt = "tool")
```

A.1.1 PRISMA Flow Diagram

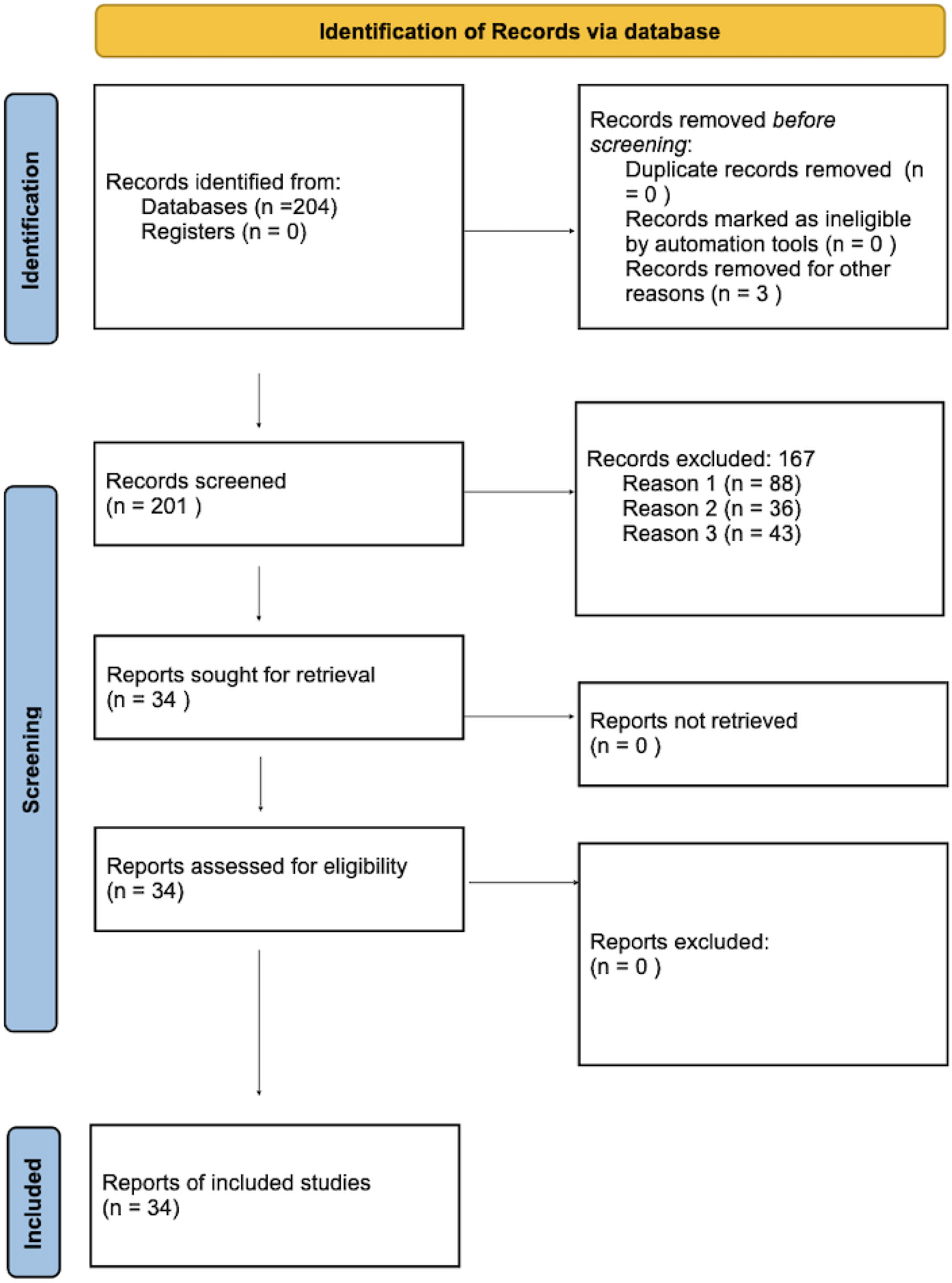

Figure A.1: PRISMA flow diagram showing the screening and selection process adopted and modified for patents (Page et al., 2021). Licensed under CC BY 4.0: https://creativecommons.org/licenses/by/4.0/

A.2 Requirement Specification

Table A.1: *Requirement specification*

	Date: 2025-04-03						
	Criterion	Description	R/W	Target value	Unit	Verification	Demander
1.		**Robustness**					
	1.1	Specified Batteries	R	3	Batteries	On-site testing	Industry
	1.2	Other batteries	W	> 3	Batteries	On-site testing	Industry
	1.3	Damaged batteries	W	> 3	Batteries	On-site testing	Industry
2.		**Process time**					
	2.1	Time	R	≤ 20	Minutes	Calculations	Industry
	2.2	Time	W	≤ 10	Minutes	Calculations	Industry
3.		**Safety**					
	3.1	Scatter inside modules	R	None	(1/0)	On-site testing	Industry
	3.2	Overheating	R	< 90	°C	—	Industry
	3.3	Distance from modules	R	≤ 20	mm	CAD geometry	Industry
	3.4	Hazardous emissions	R	None	(1/0)	—	Industry
4.		**Destruction**					
	4.1	Destruction	R	≤ 10	%	CAD geometry	Industry
	4.2	Destruction	W	$= 0$	%	CAD geometry	Industry

A.3 Elimination matrix

Table A.2: Elimination matrix

Created: 2025-04-07					**Elimination criteria**	Page 1
					+ Yes	
					- No	
					? Information missing	
					! Check requirement spec.	
Concept	**Elimination req.**				**Comments**	**Decision**
	Robustness	Process time	Safety	Destruction		
A	+	+	?	?		Yes
B	?	?	?	+	Unclear temperature for polyurethane	Yes
C	?	?	+	+		Yes
D	+	?	-	-	Too destructive and uncontrollable	No
E	-	-	+	+	Polyurethanes variability creates uncertainty	No
F	-	-	+	+	Polyurethanes variability creates uncertainty	No
G	?	?	-	?	Uncontrollable	No
H	+	+	-	?	Could pass through the modules	No
I	-	-	?	+	Polyurethanes variability creates uncertainty	No
J	?	-	+	+	Takes too long	No
K	+	+	+	?		Yes
L	+	+	+	?		Yes

A.4 Pugh matrix

A.4.1 Pugh matrix 1

Table A.3: Pughmatrix 1

Created: 2025-04-10	Pughmatrix (It 1)				
Requirements	**Concept**				
	A	B	C	K	L
Robustness	R	-	-	+	+
Process time	E	-	-	+	+
Safety	F	0	+	0	+
Destruction	E	+	+	0	0
$\sum +$		1	2	2	3
$\sum 0$		1	0	2	1
$\sum -$		2	2	0	0
Net sum		-1	0	2	3
Rank		4	3	2	1

A.4.2 Pugh matrix 2

Table A.4: Pughmatrix 2

Created: 2025-04-10	Pughmatrix (It 2)				
Requirements	**Concept**				
	A	B	C	K	L
Robustness	-	-	-	-	R
Process time	-	-	-	0	E
Safety	-	-	0	-	F
Destruction	0	+	+	0	E
$\sum +$	0	1	1	0	
$\sum 0$	1	0	1	2	
$\sum -$	3	3	2	2	
Net sum	-3	-2	-1	-2	
Rank	3	2	1	2	

A.4.3 Pugh matrix 3

Table A.5: Pughmatrix 3

Created: 2025-04-10	Pughmatrix (It 3)				
Requirements	**Concept**				
	A	B	C	K	L
Robustness	+	-	R	+	+
Process time	+	-	E	+	+
Safety	-	-	F	-	0
Destruction	-	0	E	-	-
$\sum +$	2	0		2	2
$\sum 0$	0	1		0	1
$\sum -$	2	3		2	1
Net sum	0	-3		0	1
Rank	2	3		1	1

A.5 Quantification of requirements

Table A.6: Quantification of the requirements

Robustness	**Weight**	**Process time**	**Weight**
Can handle 20% of batteries	1	< 20 minutes	1
Can handle 40% of batteries	2	< 18 minutes	2
Can handle 60% of batteries	3	< 16 minutes	3
Can handle 80% of batteries	4	< 14 minutes	4
Can handle 100% of batteries	5	< 12 minutes	5
Probability fire or damaged cells	**Weight**	**Destruction**	**Weight**
[30–40] %	1	< 8%	1
[20–30] %	2	< 6%	2
[10–20] %	3	< 4%	3
[0–10] %	4	< 2%	4
0 %	5	0%	5

A.6 Kesselring matrix

Table A.7: Kesselring matrix

Created: 2025-04-16	Kesselring matrix										
	Concept										
Requirements	w	v	t	v	t	v	t	v	t	v	t
		Ideal		A		C		K		L	
Robustness	0.25	5	1.25	3	0.75	2	0.50	5	1.25	5	1.25
Process time	0.17	5	0.83	4	0.67	1	0.17	5	0.83	5	0.83
Safety	0.50	5	2.50	3	1.50	5	2.50	2	1.00	4	2.00
Destruction	0.08	5	0.42	4	0.33	5	0.42	4	0.33	3	0.25
T (Total weighted value)		20	5.00	14	3.25	13	3.58	16	3.42	17	4.33
T/T_{ideal}		1.00	1.00	0.70	0.65	0.65	0.72	0.80	0.68	0.85	0.87
Rank			-		4		2		3		1

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