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CONCEPTUALIZING A SAFE, MANUAL DISASSEMBLY LINE FOR RECHARGEABLE CONSUMER ELECTRONICS BATTERIES

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CONCEPTUALIZING A SAFE, MANUAL DISASSEMBLY LINE FOR RECHARGEABLE CONSUMER ELECTRONICS BATTERIES

BY

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ABSTRACT

Despite the market size and substantial demand for rechargeable consumer electronics batteries (RCB), successfully disassembling and recirculating RCBs in their end-of-life stage (EOL-RCBs) remains inadequate. This inadequacy is due to health and environmental risks associated with these processes. This study systematically investigates the risks of a manual hand tool drill battery disassembly to identify the Shortest Paths to Failure (SPTFs). These SPTFs are the subject of risk mitigation measures which are incorporated in developing a low-resource, safer, manual RCB disassembly line. This process follows the objective of assigning extracted EOL-RCBs to recirculation strategies to extend their product life based on a battery degradation assessment. Implementing the conceptualized low-resource workstations significantly improves worker safety and reduces the need for newly manufactured batteries as the operational lifespan of existing batteries is extended. This represents an essential further step towards a circular economy and zero-waste society.

Keywords:

battery disassembly, manual disassembly, recirculation, risk identification, circular economy, rechargeable electronics battery

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LIST OF ABBREVIATIONS

BMS	Battery Management System
DAQ	Data Acquisition
DIN	German Institute for Standardization (Deutsches Institut für Normung)
EIS	Electrochemical Impedance Spectroscopy
EN	European Norm
EOL	End-of-life
EV	Electric Vehicle
EVB	Electric Vehicle Battery
E-waste	Electronic Waste
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
GWP	Global Warming Potential
HAZOP	Hazard and Operability Studies
HRA	Human Reliability Analysis
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization

LIB	Lithium-Ion Battery
PHL	Preliminary Hazard List
PPE	Protective Personal Equipment
RCB	Rechargeable Consumer Electronics Battery
SOH	State of Health
SPTF	Shortest Path to Failure
SWIFT	Structured What If Technique
VDI	Association of German Engineers (Verein Deutscher Ingenieure)

CHAPTER 1: INTRODUCTION

The growing demand for battery-powered devices necessitates more effective battery resource management methods to lessen the dependence on raw materials and extend the lifespan of already manufactured products [1,2].

1.1 Motivation

Current recirculation processes for rechargeable consumer electronics batteries (RCBs) in their end-of-life stage (EOL-RCBs) are inadequate for efficient component recovery due to their health and environmental risks [3,4]. While the recyclability of electric vehicle batteries is discussed in papers such as those written by Glöser-Chahoud et al. and Richa et al. [5,6], the long-established RCB market remains unaddressed. According to Precedence Research, the rechargeable battery market (valued at more than 110 billion USD) is projected to grow over 5 % per annum [7]. This includes both the electric vehicle battery and the consumer electronics segments. This study addresses the RCB disassembly market specifically. SOFEAST, a supply chain control agency, identified lithium-ion batteries (LIBs) as the most prevalent type of RCBs [8]. On top of that, the American Chemical Society reported that the recycling rate of these LIBs is a mere 5 % [9]. Despite this market size and the substantial demand for RCBs, successful disassembly and recirculation processes are still lacking for batteries such as those installed in hand tool drills, laptops, and other portable consumer electronics. This inadequacy is a reflection of challenges in the EOL-RCB dismantling process arising out of the significant lack of information on proper EOL-RCB recirculation options, as identified by Gu et al., and hazards within the process [10]. During the disassembly, health and safety risks are encountered such as toxic substances exposure from nickel, lead, and other “secondary pollution” [11] (i.e. waste gas), and sudden fire outbreak hazards caused by residual battery charges [11,12]. In addition, the batteries’ electrolytes are composed of flammable and volatile substances that are capable of igniting at room temperature [13]. Furthermore, the time intensiveness of a manual disassembly cycle time prevents any meaningful financial benefits from being reaped from the recirculation process, rendering it an unviable business venture. The combination of these risks, coupled with the lack of low-cost labor training, poses significant economic risks for companies, putting their reputation at risk if labor is severely harmed or the facility is damaged due to insufficient training and process safety. Therefore, RCB disassembly is neither socially nor economically attractive.

1.2 Objective and Structure of the Study

Implementing a manual RCB disassembly line may reduce the need for new batteries and lessen the dependency on “critical materials” [14], such as cobalt, lithium, and nickel, as defined by the U.S. Geological Survey [4, 14]. EOL-RCB recirculation procedures, rather than material recovery or new material procurement, can increase revenue through cell and component reuse and remanufacturing owing to their far less energy-intensive needs [15].

This master’s thesis will design a fully manual, secure, and efficient disassembly line prototype. The main development objectives include creating comprehensive risk identification, addressing hazards by process design, ensuring worker safety, and exploring opportunities for future automation.

The goal of this thesis is to enhance sustainability within the mechanical engineering industry. It recognizes social responsibility as an integral pillar of sustainability, along with the environmental and economic dimensions [16]. This thesis targets all stakeholders involved in RCB manufacturing, dismantling specialists, the broader mechanical industry, as well as policymakers and legislators involved in worker safety and value chain regulation. The integration of this conceptualized disassembly line has the potential to increase revenue, with ample opportunities for automation, resulting in growth of the RCB recirculation industry. By implementing a safe EOL-RCB disassembly process, the aim is to improve operator safety. Due to the considerable resource value, high demand for extracted components, and economic necessity for labor particularly in developing countries, the disassembly will be completed either with or without a safe process line.

The overarching objective of this study is to mitigate the unsustainable practice of landfilling RCBs by incorporating recirculation strategies. This will take the current community one step closer to a circular economy and a zero-waste society. This work emphasizes that achieving these long-term goals and improving the environmental friendliness of products and processes begins by prioritizing people and creating a safe environment for them.

CHAPTER 2: STATE OF THE ART

This chapter provides foundational information on the terminology used, a comprehensive literature review, and a description of the state of the art of the examined RCB disassembly procedure.

2.1 Definition of Key Terms

To establish a common understanding of the key terms employed in this master's thesis, four expressions are defined: consumer electronics, end-of-life, state of health, and recirculation.

Consumer electronics refers to products with non-commercial, private use, such as laptops or smartphones [17]. Within the scope of this research hand tool drills are used by individuals for utilitarian purposes. Therefore, hand tool drills are not primarily regarded as power tools but are classified as consumer electronics. Additionally, the greater the homogeneity among a large RCB quantity, the greater the concentration, the higher the possible degrees of automation, and the less need for manual work. Thus, this research focuses on small quantities of identical RCB models, called "non-concentrated" material.

EOL (end-of-life) indicates the moment when a product no longer meets the needs of its last user [18]. In this work, EOL denotes the final stage in a product's operating life and, specific to batteries, the point at which it is disposed of by its last user.

SOH (state of health) of batteries describes the condition of a battery relative to its initial state. It is commonly defined by the ratio of aged to initial battery cell capacity (Ah for batteries with lower capacities or Wh, which is mainly used for larger batteries such as EVB), representing the capacity change [19,20]. However, there are other approaches considering resistance, impedance, or voltage profiles for experimental approaches, or the utilization of Kalman filters or Neural Networks for adaptive SOH estimations [21]. Details on these methods can be obtained in the works by Berecibar et al. [21] or Pradhan and Chakraborty [22]. Wear, temperature influences, and high numbers of charging cycles represent causes that deteriorate the condition of the battery cells and thereby lower the SOH percentage [23]. This metric supports the determination of further battery cell utilization possibilities. **Recirculation** in this thesis involves reintegrating components and resources into the product life cycle according to the ten R-strategies outlined by Potting et al. [15]. Arranged according to descending aspiration these are: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover [15]. This study uses Potting et al.'s terminology as a baseline, excluding the first three R-strategies that pertain to the product development phase not covered by this research [15]. The remaining seven strategies support minimizing waste and promoting a circular economy [15]. Potting et al. distinguish between extending product lifespans and material-level reuse, such as recycling and recovery. This is exemplified by processes like grinding water bottles onto particle level and reforming, and melting, those into reused water bottles, while recovery involves energy use through incineration [24]. In contrast to this, Potting et al. suggest that extending lifespans and reintegrating products or their parts into their product life cycle again are superior strategies [14]. Therefore, this study uses "recirculation" and "to recirculate" to mean extending a product's operational lifespan, and the respective middle five R-strategies.

2.2 Literature Review on Battery Disassembly and Risk Identification

Before the development of the EOL-RCB disassembly line, existing approaches are reviewed to identify the exact research gap. Many scientists have contributed to this research field by instructing similar battery disassembly procedures, explaining battery hazards, or providing automation approaches. The following will provide an overview of the established methods and approaches to battery disassembly rooted in these research contributions and is followed by an overview of methods for risk identification.

2.2.1 Overview of Literature on Battery Disassembly and its Implications

Wegener et al. have conducted research on disassembling a LIB to derive a disassembly guideline and design a dismantling workstation. The entire procedure comprises the dismantling of an electric vehicle battery (EVB) and subsequent recycling of the battery cells to retrieve and recover valuable materials. Wegener et al. define dismantling steps while following a non-destructive and non-hazardous approach. By employing a priority graph, the researchers derive a sensible sequence of dismantling operations. The final sequence begins with the removal of screws and the battery's covering, continues with a determination of the battery charge status, and concludes with the retrieval of the battery stacks. Based on this sequence, Wegener et al. recommend using one single workstation to avoid moving the heavy EVB and propose a possible approach involving a robot accompanied by a single human worker, the former responsible for unfastening the nuts and screws while the latter takes over the remaining tasks. While the methodology is nonetheless partially applicable to RCB disassembly, the core objectives - obtaining "secondary raw material" [25], by dismantling or grinding battery cells, and working with larger-scale EVBs - represent two of the major differences between conducted research and that of this thesis. Specifically, RCBs can be lifted and moved with relative ease, which implies that the number of workstations for RCBs will be subject to discussion. Despite the discrepancy in battery sizes similar risks to the workers remain due to the current and hazardous substances. [25]

Cerdas et al. address the common practice of recycling and grinding batteries to particle level which decreases the quality of the material. The objective of the research of Cerdas et al. is to develop a disassembly sequence for an EVB to avoid shredding, enabling higher material quality and thus higher revenue. Cerdas et al. point out the economic advantage of separating parts of batteries such as the cells or battery management systems as opposed to shredding the battery as a whole. Furthermore, in contrast to other papers, Cerdas et al. mention several strategies introduced by Potting et al. [15]. Moreover, that work provides several references to further literature on the disassembly planning and consideration factors and draws close references to the aforementioned work by Wegener et al. After conducting a series of experiments to obtain information for product analysis, Cerdas et al. found that the EVB structure is similar among different manufacturers. Based on the work of Wegener et al. and other literature, the paper derives automation potentials by employing the two assessment categories "automation capability" and "necessity of automation". The resulting diagram shows that close to no dismantling operation within the disassembly sequence has both a high automation capability and a high automation necessity. Most of the tasks have a limited automation capability and, on average, an even lower automation necessity value. It is important to note that the dismantling procedure, and thus, the diagram, encompasses operations that have a close to zero necessity for automation, and a negative automation capability or negative necessity value and mediocre capability value. The applicability of Cerdas et al.'s findings for this master's thesis is restricted, as the paper research examines EVB. [26]

Duflou et al. use an economic approach to evaluate the feasibility and the added value of dismantling a product [27]. For Duflou et al. the residual value as well as the estimated maximum operation time play critical roles in the reasoning for disassembly [27]. However, this master's thesis shows that there is not only an economic value to maximize but also a social and an environmental one associated with not disassembling. By dismantling a product and applying one of the R-strategies proposed by Potting et al. the already manufactured resources can be harnessed, mitigating new procurement and exploitation of new resources, enabling more sustainability.

A study by **Kampker et al.** developed battery remanufacturing approaches based on the battery cell shape, such as cylindrical, pouch, or coin. Although the study briefly addresses battery pack disassembly and a battery condition and SOH assessment, these aspects are not the primary focus. Instead, the research provides detailed procedures on battery cell disconnection methods, re-joining technologies, reassembly steps, and materials required for creating a remanufactured battery module. In conclusion, Kampker et al.'s work focuses on EVB disassembly, sorting, and the final remanufacturing process. [28]
This ties in with the topic of this thesis but also highlights the need for research on disassembly processing and remanufacturing of RCBs, rather than EVBs.

Schäfer et al. [29] propose a remanufacturing process for extracting and directly replacing battery cells from one EVB into a different EVB module, as detailed in their research. Starting from extracting battery modules from the EV casing, detaching welded cell connectors, removing covers, replacing old with new cells, and finally restoring cell connections in the battery module. It provides a manufacturing-oriented perspective as well as detailed considerations such as the necessary drilling depth to cut the welded battery connectors. Furthermore, the production process is considered, and the issue of irreversible production operations and non-detachable connections is addressed. In conclusion, the work by Schäfer et al. targets a similar objective to the one addressed in this study. However, the paper focuses on the extraction and replacement of single battery cells, whereas this thesis does not concentrate on the separation of the battery cells from each other, focusing rather on the pack disassembly and integration of SOH, including recommendations for subsequent treatment to recirculate the battery into its life cycle. [29]

The research of **Li et al.** takes the disassembly process of EVBs one step further by presenting a method of automated screw detection and unscrewing [30]. However, unfastening is a small fraction of the total work and thus, the findings by Li et al. can be utilized to a limited extent.

Chen and Shen researched the rapid assessment of the capacity and internal resistance of single cylindrical battery cells to classify them as reusable or waste. They employed X-ray radiographic scanning to visualize and assess the internal structures of the battery cells. According to Chen and Shen, a sharper radiographic image with less blurring indicates a better battery condition. This assumption was validated by measuring the internal resistance, using a threshold of 150 milliohms for 18650-type battery cells. Cells with an internal resistance below this threshold are deemed reusable, while those with higher values are designated as waste. This study did not investigate the disassembly process to extract the cells from RCBs. [31]

Furthermore, as outlined in subsequent chapters, internal resistance alone is not a sufficiently representative value for the SOH of a LIB and is therefore unsuitable as a method to validate SOH results. Nonetheless, for an initial rough estimation, the internal resistance can provide sufficient information and significance. The swift processing time noted in the paper excludes the time for the X-ray radiographic imaging process, considering only the algorithm computation time. While Chen and Shen's study presents a novel approach to assess the condition of 18650 batteries, it has shortcomings in terms of accuracy, time, and applicability to other battery cell types. Consequently, these findings do not apply to this master's thesis which targets the RCB disassembly and assessment process with minimal resources.

The work of **Tarascon and Armand** identifies the structure of liquid rechargeable lithium-ion cylindrical, coin, or prismatic battery cells, commonly installed in RCBs as cylindrical cells [32], educating about internal components.

Liang et al. observed that laptops, smartphones, other consumer electronics, as well as power tools manufactured around the year 2000 commonly employ liquid electrolytes as well [33].

A study on batteries structure by **Li et al.** yields, that substituting the liquid electrolyte with a solid-state "polymer membrane blended with a Li salt" [34] increases safety. This is due to a reduced amount of highly flammable electrolytes within a solid-state polymer compared to solely liquid electrolytes. [34]

Xu et al. differentiate between primary lithium batteries and secondary lithium batteries, as primary lithium batteries do not encompass toxic substances, and secondary lithium batteries do not contain solid metallic lithium but rather toxic liquid lithium-ion electrolytes. This distinction is comparable to the two following categories: solid-state electrolytes and liquid-state electrolytes in LIBs. In most of the cases, RCBs belong to the class of secondary, liquid electrolyte lithium batteries according to Xu et al. [35]

While the market for portable RCBs developed into flatter, lighter products, lithium-ion batteries are being substituted by solid-state lithium-ion polymer batteries [33]. High-energy portable devices, such as hand tool drills, still utilize LIB, as these do not undergo optimizations in terms of lightweight and increased safety during user operation. Smartphones and laptops are optimized continuously as these types of consumer electronics devices develop into constant companions of individuals. **Gu et al.** report that the majority of consumers, however, lack information on where and how to dispose of or recirculate used batteries [10]. To increase this rate of recirculated RCBs and achieve progress toward a circular economy, proper information and education about both EOL treatment and the dangers of EOL-RCBs are necessary [10].

Regarding the risks to individuals, **Harter et al.** have published a technical report in which electrical hazards of LIB disassembly are examined and approaches to risk control are provided. This research highlights the risks of automotive LIBs due to residual charges, which can lead to electric shocks or arc flashes. Electric shocks occur when a person's body becomes part of an electric circuit, while arc flashes occur when electric arcs explosively release energy. Harter et al. emphasize the importance of personal protective equipment (PPE) for workers exposed to electrical hazards during battery disassembly. PPE includes flame-resistant or rubber gloves and sleeves to insulate workers and prevent electrical charges from flowing through their bodies. Harter et al. also suggest avoiding work on energized conductors and ensuring that electrical systems are operated in hazard-free environments. Additionally, they provide guidelines on risk categories and PPE requirements, similar to Oak Ridge National Laboratory guidelines. For EVBs, risks, such as self-heating and self-ignition due to thermal or mechanical triggers are listed. Control circuits are installed to regulate voltage and current, preventing overcharging and hazardous charging rates that could cause heating or ignition. [36]

The report by **Wang et al.** [37] sheds light on some of the hazardous situations encountered in informal recycling facilities in China such as the fire outbreaks due to the removal of chips from printed circuit boards. In over 3300 organized facilities, electronic waste (e-waste) is illegally dismantled in Guiyu, China. Despite the lack of knowledge about procedures, hazards, and lack of PPE, the objective is to find valuable materials and parts in the waste, such as LIBs. Batteries are of higher importance than other parts, as they yield more revenue than cables, screws, or other parts. [37]

Additional information on the handling, hazard, or fire code standards, and about different rechargeable batteries can be found on the website of the Rechargeable Battery Association[1].

[1] https://www.prba.org/areas-of-focus/regulations-and-standards/ [last accessed on 05/29/2024]

2.2.2 Overview of Risk Identification Methods

To effectively address hazards during manual EOL-RCB disassembly, they must be systematically identified before process development. The International Electrotechnical Commission (IEC) standard IEC 31010 provides methods for each risk assessment phase [38]. According to the risk identification stage of IEC 31010, Checklists, Failure Modes and Effects Analysis (FMEA), Hazard and Operability Studies (HAZOP), Scenario Analysis, and Structured What If Technique (SWIFT), alongside Human Reliability Analysis (HRA) and Fault Tree Analysis (FTA) can be used to identify risks in manual RCB disassembly. In the following, all methods are briefly described according to IEC 31010 [38].

Checklists

Based on experience and best or worst practices, checklists serve as holistic tools to categorize risks according to selected properties, such as risk source or effect. Typically, checklists organize risks into categories, such as political, economic, ecological, social, or technological risks. Choosing appropriate categories allows for effective risk identification specific to the respective use case. Both bottom-up and top-down approaches are commonly employed. Qualitative checklists are used in the early development phase and often serve as input for other risk assessment methods. [38]

Failure Mode and Effect Analysis (FMEA)

A Failure Mode and Effect Analysis is utilized to collect all possible failure modes and evaluate their causes, probability of detection, probability of occurrence, and effects. The process is standardized in the standard IEC 60812 which outlines the necessary steps of a planning phase, an execution phase, and a final documentation segment [39]. The planning phase determines the scope of the analysis, performs a structural analysis, and defines the main criteria for subsequent risk criticality evaluations. The execution phase involves thoroughly identifying and analyzing failure modes, their effects, and deriving their failure criticality. Typically, a bottom-up approach is used to analyze potential failures and failure modes of each component. A risk priority number is calculated as the product of three values: severity, probability of occurrence, and probability of detection, each ranging from 1 to 10. This results in a risk priority number ranging from 1 to 1000 for each failure mode. Documentation involves a comprehensive worksheet listing failure modes, assigned values, suggestions for improvement, and other pertinent information. Thus, FMEA is an exhaustive quantitative technique for determining risk priority numbers for products, processes, and more, allowing for the prioritization of actions to mitigate hazards. FMEA commonly focuses more on post-development failure modes, complicating the assessment of external risk factors. [39]

Hazard and Operability Studies (HAZOP)

The Hazard and Operability Study is conducted to assess the safety, health, and environmental hazards or quality deficiencies of an operation after the design and development stage, for example during the operation phase [40]. Working with detailed documents describing the system enhances the process. The methodology is to find physically feasible deviations from the designer's intentions by utilizing guidewords such as "more", "less" or "reverse", as provided in the standard IEC 31010 [38]. The process begins with the sectioning of the examined process. This is followed by the selection of operation parameters which are combined with guidewords to develop variations. These variations are employed to derive possible causes and effects. Finally, other guidewords are paired with the parameter and the process is iterated [40]. Consequently, HAZOP is a qualitative technique carried out in a workshop setting that defines potential risks on a strategic or operational level by identifying deviations from the original designer's intention [38].

Scenario Analysis

Scenario Analysis is employed to assess risks and their impact at a strategic or operational level, to achieve a qualitative result in a narrative format. It is of particular benefit to consider environmental, technological, or regulatory changes that may affect the scope under investigation, as well as to predict emergency circumstances. Therefore, it is mainly utilized at a corporate or strategic level once the system being investigated exists and is in a later, operational stage of development. The strength of Scenario Analysis is its capacity to explore a wide range of potential consequences. To achieve this, data on past, present, and future prospects, in conjunction with growth, development, or distribution models, and justified estimations based on past events can be involved and assessed to develop scenarios. [38]

Structured What If Technique (SWIFT)

This qualitative technique is conducted through a verbal discussion in which guidewords pertinent to the investigated system are combined with “what if” or “how could” starts of the record. Guided by these prompts, the participants engaged in brainstorming and discussions progress to identify risk sources, past incidents, and the frameworks of the system. The objective of this process is to investigate the effects of and resulting risks due to certain system adaptations. This illustrates the similarities between the SWIFT and the HAZOP methodologies. However, SWIFT is typically employed to evaluate the broader system performance and system operation, whereas HAZOP addresses detailed design choices and is a more comprehensive technique than SWIFT [38]. Nevertheless, this approach yields a record of risks and associated preventative or reaction risk control measures. Furthermore, Card et al. suggest that this technique should be employed in conjunction with subsequent procedures such as a FMEA, FTA, or HAZOP. [41]

Human Reliability Analysis (HRA)

A Human Reliability Analysis can be employed to assess how human behavior influences the level of risk. This analysis comprises several steps, including the modeling of the system, the identification, and classification of potential human errors, the analysis of interdependences, the evaluation and quantification of the occurrence probability of human error and the development of human error mitigation strategies. By investigating human error and the factors influencing the operator's performance the aim is to reduce the number of accidents or undesired events. Typically, it is utilized on an operational and tactical level to address each process step, necessitating a detailed understanding of the operations and implemented mechanisms. A HRA can be applied at a later stage during system adaptations or process optimization to yield an accurate qualitative list of human errors, pertinent performance consequences, and an assessment of the identified risks. [38,42]

Fault Tree Analysis (FTA)

A Fault Tree Analysis is a proven systematic technique to identify the root cause of product or process failure described in the standard IEC 61025. Ericson recommends performing a FTA in an early stage of the development and design phase to minimize design adaptation costs [43]. As a proactive graphical measure, FTA aims to estimate and prevent system failures or hazards. It begins with an undesired critical top event at the top of the tree diagram and identifies direct precipitating causes. By employing Boolean operators such as OR, AND, EXCLUSIVE OR, and others, the connections between causes are established. Next to the operators, the events can be distinguished in intermediate events as rectangular boxes or basic events which specify a root cause in a circular shape or other event types. Lastly, undeveloped events are important to mention, as they are displayed in diamond-shape when an event lacks information or is subject to further investigation that is not performed within the framework because the added value is negligible to the research objective. Following the top-down approach further and decomposing causes to their potential causes eventually leads to the determination of root causes. However, Kritzinger recommends "breadth before depth" [44, p. 67] to explore the number of different causes before tracing singular paths back to their root causes to enable completeness. The resulting logic structure can then be utilized to analyze the lengths of different paths from various root causes to the top event. The shortest path represents the critical path. This logic tree helps to highlight critical areas and the visualization of recurring basic events, which allows for the derivation of appropriate and effective risk measures. The qualitative tree analysis represents the main step and shows the option to be supplemented with justified quantitative values for the probabilities of event occurrences. In the context of the examined disassembly process, safety deficiencies and related risks can be determined and assessed using FTA. [43,44]

Preliminary Hazard List (PHL)

A Preliminary Hazard List pursues the target of enabling system design for safety and therefore creates a list of system hazards in the early concept and development phase [45]. This method starts by collecting insights gained from experience with the investigated or similar systems, information on the system components, and general hazard categories of similar structures of this kind, as provided in hazard checklists in standards such as the European Version (EN) from the German Institute for Standardization (DIN) DIN EN 1050 or the

International Organization for Standardization (ISO) ISO 12100. These checklists, such as listings of potential human hazards or energy sources, are used to compare the examined system components to the checklists to develop the final system-specific hazard list [45].

2.3 Current Status of Use Case

As the U.S. and several other nations did not ratify the Basel Convention, as opposed to European states, the export of waste with dangerous substances is still legal [46]. The Convention prohibits the export of hazardous waste without the receiving country's consent, or if an environmentally conscious treatment of the waste is justified as improbable in the receiving country [47]. This leads to the legal export of hazardous waste to other countries, in which labor for repair, refurbishment, or recycling is significantly cheaper than in the U.S. or other developed countries [48,49]. Also, the low-labor-cost import countries possess less strict environmental, safety, or health regulations or policies on the matters of hazardous waste treatment or disposal and this represents another advantage to exporting electronic waste with hazardous substances [48,49]. However, prevailing conditions and the constant objective of minimizing costs culminate in the choice of untrained people performing electronic dismantling [48,49]. Dhanda and Peters report that refurbishment of e-waste that is conducted in prison facilities and framed the sometimes inadequate conditions for people in hazardous waste importing countries as deciding between “poverty or exposure to toxins” [48]. The frequent lack of qualification of, sometimes temporary, workers denotes another critical aspect of current disassembly procedures [50].

Additionally, the status of the disassembly process represents significant optimization potential. However, the available literature that describes currently conducted recycling or disassembly procedures is limited. Bryg et al. state that in developing countries the separation process of batteries from products is still entirely manual and is in some cases lacking proper working conditions and safety [51]. Cerdas et al. confirm these typically manual disassembly procedures [26]. Ghazilla et al. describe the recycling operation in Malaysia as a usually unofficial small-scale endeavor that turned into a more export-oriented larger business within the last years [52].

In comparison, the United Nations University reported the growth of the informal e-waste recycling sector in Chinese regions despite the lack of knowledge about the associated health and safety hazards [37]. Furthermore, Wang et al. found that the money for training or equipment is usually lacking, which results in unqualified individuals performing the dismantling and material recovery without sufficient awareness of the risks or use of protective equipment. Only simple tools such as “hammers, chisels and screwdrivers” [37] are utilized. On the other hand, Wang et al. also report formal dismantling organizations, which focus on larger EOL electrical appliances such as televisions and are therefore not relevant to this master’s thesis. [37]

Public Information Agencies such as CNN report on the situations in China as well as in India as dismantling labor which shows a deficit of coordination, organization, and personal protective equipment [53,54]. Similarly, the Konrad Adenauer Foundation published an article on the dismantling and e-waste treatment situation in India, which does not report any working equipment; no tables or tools, and repeatedly, the lack of personal precautions [54]. As a takeaway for the further progression of this study, the sources are summarized in the assumptions of currently lacking work furniture, work equipment other than hammers, chisels, and screwdrivers, a lack of awareness about the health and safety risks and PPE, lacking process understanding and training.

2.4 Derivation of Research Questions

In most cases, the reviewed literature refers to EVB, but according to the organization Precedence Research the battery market not only for EVB but for RCBs in general, is growing [7]. This master's thesis will focus on RCBs with the example of hand tool drill batteries. There is close to no literature that provides individuals with guidelines on dismantling small consumer batteries. The literature focuses on subsequent recycling methods such as hydrometallurgical procedures or recovery, as elaborated upon by Xu et al. [35]. However, this recovery of materials is according to Potting et al. not the desirable level of strategies, but extending the lifespan of a product and its parts is to be aimed for [15]. Therefore, in contrast to the existing literature, this master's thesis seeks to answer the question of a recirculation method for EOL-RCBs and enabling an extended lifespan of the hand tool drill batteries and their parts. Within this development, the process safety of individuals represents a key consideration. To accommodate for this objective, risks and critical errors are identified, which this disassembly guideline aims to reduce.

→ What are the safety and health risks to individuals during the disassembly of a hand tool drill battery?

→ How can the identified risks be reduced during the disassembly of a hand tool drill battery?

Also, this work proposes prospects for further treatment of the battery cells, dependent on examined cell properties, which are subject to the results of a SOH assessment. These further utilization possibilities can be categorized according to the R-strategies by Potting et al., focusing on the extension of the battery lifespan: repurpose, remanufacture, refurbish, repair, reuse, or if necessary, recycle or recover [15]. The last Rs refuse, rethink, and reduce are not taken into account as they do not relate to the extension of the product lifespan, but to the development and design phase [15]. This way, this master's thesis combines the provision of dismantling guidelines with information about existing subsequent utilization options.

→ What R-categories according to Potting et al. (repurpose, remanufacture, refurbish, repair, reuse, recycle, recover) can the spent RCBs be assigned, to facilitate recirculation?

Depending on the targeted categories of further utilization, information on the SOH of a battery which is viably obtainable in a minimally equipped amenity, shall be considered. Therefore, an approach is developed to beneficially integrate SOH information to justify potential future usage scenarios.

→ How can information on the SOH of a battery be utilized in the disassembly process in environments with limited resources?

By addressing these research questions, listed in Table 1, the objective of conceptualizing a manual, safe disassembly line for RCBs is systematically approached, in discrete stages leading to the realization of this goal. The creation of this disassembly line is crucial in laying the foundation for future advanced automation with robot technology and integrated artificial intelligence, which will maximize the efficiency of RCB resource management in the years ahead.

Table 1: Overview of the research questions addressed in this study

Name	Research question
RQ1	What are the potential safety and health risks to individuals during the disassembly of a hand tool drill battery?
RQ2	How can the identified risks be reduced during the disassembly of a hand tool drill battery?
RQ3	What R-categories according to Potting et al. (repurpose, remanufacture, refurbish, repair, reuse, recycle, recover) can the spent RCBs be assigned, to facilitate recirculation?
RQ4	How can information on the SOH of a battery be utilized in the disassembly process in environments with limited resources?

CHAPTER 3: METHODOLOGY

Based on the reviewed literature describing state-of-the-art procedures and findings in proximal fields of research as well as the current situation of the RCB disassembly procedures, the methodology is presented in this chapter. After deriving the leading research questions, the battery types for a practical series of battery disassemblies are presented. A description of the experimental setup follows and precedes the disassembly documentation of the examined battery models. Subsequently, the data and information yielded by the dismantling procedures are collected in post-processing.

3.1 Research Design

This study focuses on three key objectives in the development of a concept for a manual disassembly line: sustainability, efficiency, and safety. Sustainability is achieved by maximizing the reuse probability and deploying the least wasteful R-strategies to extend product life according to Potting et al. [15]. Efficiency is ensured by designing the concept to facilitate the disassembly of different battery types without the need for significant financial or labor resources. To accommodate the third objective, it is necessary to implement safety measures that mitigate and reduce the identified risk factors.

To collect the data on which the design will be based, experiments involving the manual disassembly of at least five different battery types have been conducted at the start. Integrating ergonomic and product development principles, such as the standard by the Association of German Engineers (VDI) described in VDI 2221, is crucial for the realization of an efficient manual disassembly guideline. VDI 2221 prescribes the determination of separate functions, which in this case of a disassembly, are represented by the necessary actions [55]. This series of experiments will yield which functions need to be fulfilled to extract a battery module from the hand tool drill battery pack. After the determination of functions, the dominant risk factors that require optimization can be isolated. Furthermore, VDI 2221 recommends researching solution principles, which refer to actual implementation approaches, to fulfill the identified functions. All the solution principles with their respective function will be visualized in a morphological box. Next, the standard advocates aggregation of the selected solution concepts, a synthesis of the modules into one coherent disassembly line concept [55]. This approach ensures that design choices align with established metrics, emphasizing the significance of a robust disassembly process. In conclusion, this master thesis will represent the disassembly steps for the five batteries studied as a flowchart for a generic battery pack disassembly.

3.2 Battery Samples

The following two sections cover the explanation of the selection of the battery samples as well as a subsequent presentation of the examined battery models.

3.2.1 Selection of Battery Samples

For this study, five distinct types of hand tool drill batteries have been selected to analyze structural similarities among different RCB types and broaden the guideline's applicability. These batteries were procured from the battery recycling station near the University of Rhode Island campus. Multiple spent samples were retrieved from three of these types. Three of the five types feature a tower structure as recognizable in Figure 1. Taking spent RCBs from the recycling station reflects real-world conditions for developing and optimizing disassembly procedures in this study. These batteries lack specific data on manufacture year, operational duration, charge-discharge cycles, or potential damage, mirroring the conditions experienced by workers in developing countries.

3.2.2 Description of Selected Battery Samples

The selected battery types are DEWALT XRP DC9096, Makita 1234, Makita BL1815, Ryobi ONE+ 190, and Worx WA3525, and are depicted in Figure 1. To ease the readability of the text, the batteries' model names are shortened to their manufacturer. To maintain clear identification, the two Makita models are designated as Makita1 (Makita 1234) and Makita2 (Makita BL1815). A summary of selected technical properties of the batteries is provided in Appendix A.

Figure 1: Examined types of RCBs (from left to right Makita BL1815, Worx WA3525, Ryobi ONE+ 190, Makita 1234, DEWALT XRP DC9096)

3.3 Experimental Setup

The first step resembles the setup for the dismantling series. The setup consists of optical sensors and standard workshop tools; for further disassembly, it can be supplemented with sensory gloves. This manual experimentation step does not require high-reliability criteria for the camera resolution. An initial optical inspection showed that four out of five batteries require the same torx drill-bit in the size TR10, due to visible screws on the DEWALT, Makita2, Worx, and underneath plastic covers on the Ryobi model. This leads to the first conclusion, that some standardization among different manufacturers of hand tool drill batteries exists and culminates in one common screw type for the external plastic coverage.

3.4 Battery Disassembly Experiment

Following the procurement and initial inspection, each battery model is dismantled intuitively to retrieve the battery module.

DEWALT

Once the six screws have been loosened and removed the yellow top cover is separated from the bottom. Two connected battery modules comprising six battery cells each, are visible and illustrated in Figure 2 (c). A cylindrical electrical component is mounted on top of one of the modules. Prior to any other action, it is necessary to isolate the electric circuit by cutting the visible black and red cables with pliers. Subsequently, the black bottom cover of the battery pack is rotated to a position where it is standing on one side. This facilitates access to the thin metal connector on the bottom of the capacitor cylinder, which can then be separated with pliers. Next, the bottom plastic cover can be flipped to let the battery module fall out of its case. Finally, the parts of the red covering paper can be separated and the thin metal bands connecting the two modules of six cells each can be cut. A closer examination of the battery dimensions shows that these are not typical 18650 battery cells. But the cells yield an approximate diameter of 0.9” and a height of 2” and online research yielded that these are twelve 1.2 V, 2200 mAh, Sub-C NiCd battery cells. Result: six screws, two plastic external covers, two battery packs of six cells each, and one capacitor.

Makita1

The model Makita1 is a different type of battery, a Ni-MH, which refers to Nickel-metal hydride and additionally, it possesses a different shape than the other four types by having a triangular-like base body. The lack of screws on the external plastic cover indicates a snap-fit attachment mechanism, rather than a force-fit connection. Manual application of force did not help to remove the top plastic cover, acting as a shaft from the bottom external cover, the hub. Therefore, for this battery type, it is not possible to disassemble this hand-tool drill battery without destroying one of the parts. This destructive separation can be performed with hands or by utilizing a cutting device like a saw or cut-off grinder. The last two lead to heat generation in the cutting area and will reduce the quality of the material significantly, particularly by possibly melting and charring the area. Furthermore, imprecise cutting could lead to damage to the inner parts and to the risk of puncturing or cutting battery cells or the battery management system (BMS) unit and thus, an increased risk of hazards. The disassembly of Makita1 is hence terminated. Result: This battery should not be manually disassembled.

Makita2

The first step is the loosening and removal of four screws, followed by the separation of the bottom cover from the top cover. The inner part is press-fitted into the top plastic coverage, which means that a tool, such as a chisel, is used to loosen and extract the inner pack. The inner pack displays a BMS unit on a black plastic frame on top of the battery module, as pictured in *Figure 2* (b), and a white unconnected plastic slider, which falls off independently. To reduce the risk of residual charges, the visible red cable connected to the BMS is cut. Next, the BMS must be disconnected from the battery module by cutting the metal connecting sheet with pliers. Once all thin metal bands have been cut, the black plastic frame with the BMS attached to it can be lifted from the battery module. The flexible plastic encasing on the bottom of the battery pack can then be separated. The dimensions of the battery cells, a diameter of 18 mm and a height of 65 mm, yield the identification of 18650 battery cells. Result: four screws, two plastic external covers, one battery pack of five 18650 cells, one BMS on a black frame, one slider, and one soft plastic cover.

Ryobi

Following the identification of small plastic covers for the screws and their subsequent removal, the five screws, four positioned along the sides, and one situated at the tip, are loosened and removed. This allows the top cover to be separated from the bottom thereby revealing the BMS mounted on the battery module. It has a white plastic tower with metallic connectors, which can be seen in Figure 2 (d). The next step is to remove the two plastic side clamps from opposite sides of the bottom battery pack. Afterward, the five red and one black cables must be severed to interrupt the electric circuit. Then the entirety of the green battery module, which contains the BMS, can be detached from the bottom plastic cover. Four screws can be found which attach the BMS to the battery module. These were removed by employing a cross-recess bit size 0 and the BMS was separated. Upon closer examination, two small screws have been identified, clamping the battery module casing together. Without a fine screwdriver extension or destructive separation approaches, it was not possible to loosen or remove these screws. The size of the battery cells indicated the cell type. Result: nine screws, two plastic external covers, one battery pack of five 18650 cells encased in a green frame, and a BMS with a plastic tower.

Worx

The Worx battery comprises four screws that must be loosened and removed. When the plastic cover at the bottom of the battery is removed, a thin, semi-transparent plastic layer is revealed on top of the battery module. Once the plastic sheet has been removed and the battery module extracted from the moderate press-fit of the black plastic external cover, it can be observed that a BMS is attached to the other side of the battery module. Next, the black visible cables must all be cut. The two thin metal sheets that connect the BMS to the battery module can then be grasped and cut with a wire cutter. After loosening the first connector, without disconnecting it, clasping, and cutting the second caused a small spark during the dismantling experiment and provided first-hand experience of the risks associated with handling RCBs. Nonetheless, the metal connectors were cut with a wire cutter to separate the pack of 18650 battery cells. Result: four screws, two plastic external covers, one battery pack of five 18650 cells, one BMS, one thin plastic layer.

Figure 2 illustrates the four extracted battery modules.

(a) (b) (c) (d)

Figure 2: Extracted battery modules from respective RCBs (a) extracted battery module of Worx, (b) internal parts and extracted battery module of Makita2, (c) disassembled parts of DEWALT, (d) internal parts of Ryobi and extracted battery module with screwed plastic frame

3.5 Data Collection and Analysis

The manual disassembly of these five battery types yielded important information in terms of the differences and similarities in battery structure among the models. The following three sections elaborate on the structural components and properties of the batteries, the required tools, and the general disassembly sequence for hand tool drill batteries.

3.5.1 Relevant Structural Battery Properties

The examined properties that have an impact on the further development of the disassembly guide are the number of screws, the number of battery cells, whether a BMS unit is installed, whether a tower structure is employed, and others. *Table 2* summarizes the properties of the examined battery models.

Table 2: Structural properties of the five battery models examined (identified through manual disassembly)

Property / Model	# Screws	# Battery Cells	BMS Unit	Tower	# Cables	# Metal Connectors	Case around Battery Module
DEWALT	6	12	no	yes	2	2	no
Makita1	0	-	-	yes	-	-	-
Makita2	4	5	yes	no	1	3	no
Ryobi	5 + 6	5	yes	yes	6	1	yes + screws
Worx	4	5	yes	no	1	2	yes

3.5.2 Required Tools for a Manual Disassembly

The experiment series conducted utilized a screwdriver, a torx TR10 bit, a cross-recess 0 bit, pliers, a wire cutter, and a fire extinguisher as well as battery safety bags were always nearby. As noted earlier, the Makita1 could not be dismantled with the available tools. For that, a cutting device is necessary to open the snap-fit attachment. Also, for Makita2 a screw attaching the BMS to the black plastic frame was identified, which needs a Phillips, also referred to as crosshead, size 1 bit to be loosened and removed. During the disassembly of the Ryobi model four screws were removed with a cross-recess size 0 bit, and to remove the green frame either a fine screwdriver extension with a torx TR10 bit must be employed or a cutting device like a knife, which again leads to an increased risk of harming the battery cells.

3.5.3 Derivation of a General Disassembly Sequence

Next to the differences in the necessary tools, the discrepancies in the dismantling sequence will be examined in the following paragraph. For all batteries, an initial optical inspection is the first step, which is followed by the identification of screw locations as well as the loosening and removal of the screws representing the second set of steps of the RCB disassembly for four of five batteries. For the fifth model, Makita1, the identification of screw locations yielded no visible screws and thus, led to the detection of a different non-destructively detachable connection. This step yielded no manually detachable connection without destructive and hazardous measures. Consequently, the necessity for a distinct method to disassemble the external hard plastic covers was identified. Yet, it was not implemented within the experiment due to the priority of operator safety and avoidance of destructive measures on the hand tool drill battery pack without an awareness of which internal components might be punctured or damaged. If the external covers are loose, they could be separated. However, for models such as DEWALT and Ryobi, some screws are not visible at first sight, and a backward loop is implemented to detect, loosen and remove all external screws. After the screw removal with a hand tool drill, the two plastic external covers of the RCB are detachable from each other, and the tower structure covers for Ryobi and DEWALT, or the bottom covers of Makita2 and Worx are removed. For all samples, the next step is interrupting the electric circuits by cutting all visible cables. Similarly, the connection between critical parts such as capacitors or a BMS unit and the battery module must be disconnected, which is achieved by cutting the thin metal connectors to the battery module. In case there are unconnected parts such as the plastic slider in Makita2, the side plastic clamps in Ryobi, or the thin plastic layer in Worx, they are removed next. Lastly, the residual frames, which sometimes have BMS, or plastic covers attached to them, must be removed to access the battery modules. Based on these steps, the flowchart illustrated in Figure 3 is derived and represents a disassembly sequence that can be applied to all five examined battery models to extract the battery cell module.

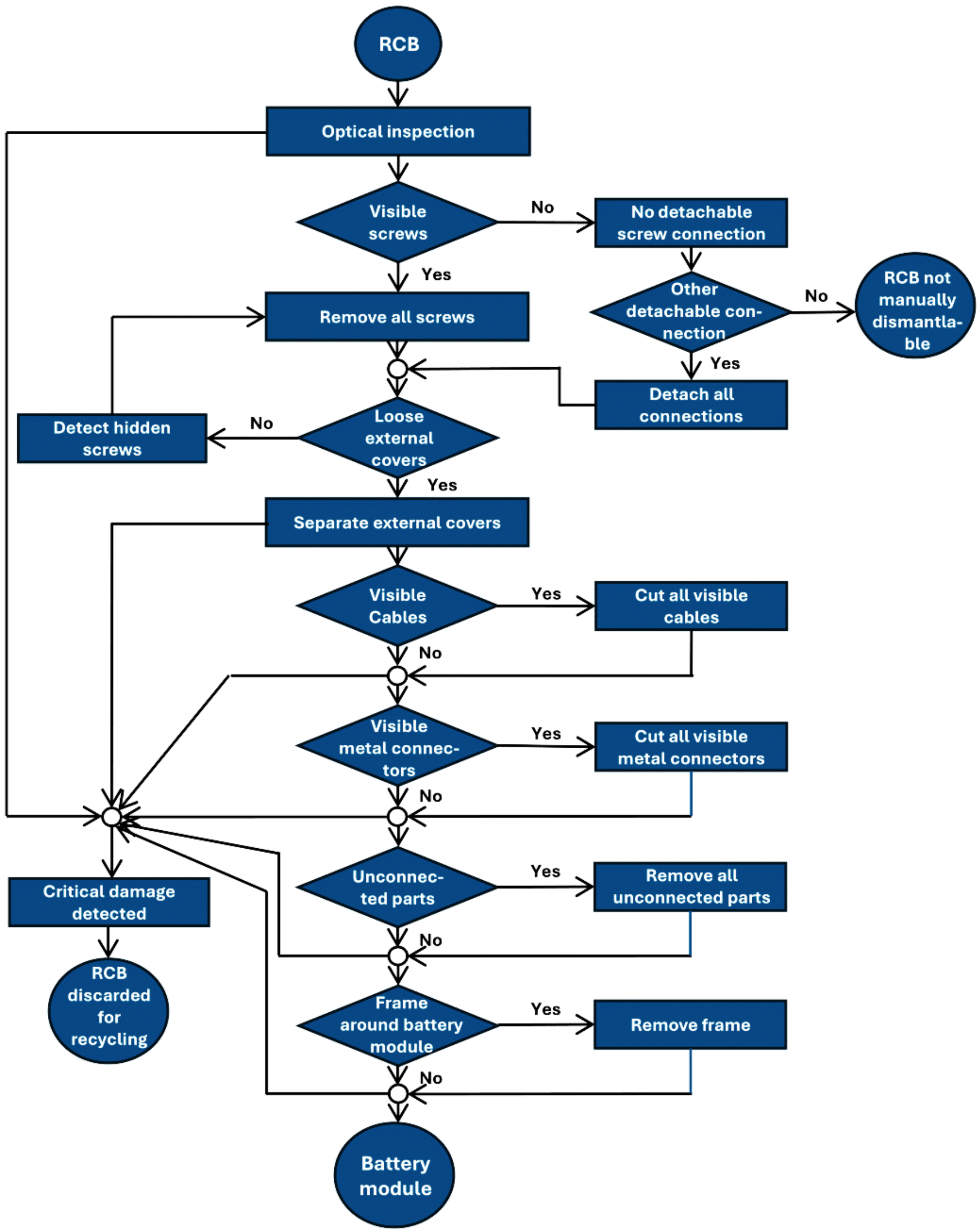

Figure 3: Flowchart of the disassembly process for the examined RCB models

3.6 Risk Identification

As a last step within the post-processing of the disassembly series, the risk exposure and hazards during the process must be addressed. Therefore, a systematic analyzing process is employed, to identify and evaluate potential risks during the process and derive measures to prevent these hazards.

3.6.1 Justification of a Risk Identification Method

To evaluate the methods described in Chapter 2.2.2, they are compared according to relevant criteria for the investigated disassembly process. To use the resulting risks of the method as a foundation for the risk mitigation concept development, the first criterion is the common time of application: in an early development phase (1) or after the system development (0). The next criterion is chosen according to the IEC 31010 standard and refers to the application level of the technique, whether it is applicable on a strategic, tactical, or operational level. As the chosen method is applied to a practical process, 1 is assigned to the operational application level and 0 to the strategic and tactical levels. Furthermore, the risk assessment represents a step before the concept and development phase, thus, a self-contained approach (1) is more desirable in this case than a method that is recommended to be only used in conjunction with another method (0). This evaluation is represented in the criterion “self-contained”. Lastly, the conducted disassembly experiments did not yield representative values for hazard or human error occurrence probabilities, nor for the probability of detection or other numerical values. Also, there is no reliable work of literature on the rates of hazardous incidents for RCBs that provides these values. Therefore, the distinction is made whether a risk identification method requires quantifying the risk (0) with values that in this case can only be estimated without any scientific justification or whether the approach can be meaningfully implemented on a qualitative level (1). According to the descriptions above and the standard IEC 31010, the methods are evaluated on a scale from 0 to 1, with 1 indicating applicability to the manual RCB disassembly under investigation and 0 indicating a less optimal approach. The resulting values are registered in Table 3.

Table 3: Comparison of risk identification methods

Criterion / Method	Time of Application	Application Level	Self-Contained	Qualitative	Sum
Checklists	1	0/1	0	1	3
FMEA	0	0/1	1	0	2
HAZOP	0	0/1	1	1	3
Scenario Analysis	0	0	1	1	2
SWIFT	0/1	0/1	0	1	3
HRA	0	0/1	1	0	2
FTA	1	0/1	1	1	4
PHL	1	0/1	1	1	4

The assignment of 1 to a criterion represents the optimal choice for the use case of a risk identification of a RCB disassembly process. Consequently, the higher the sum of all values of one method, the more suitable it is for the application purpose within the framework of this master's thesis. Table 3 indicates that FTA and PHL meet all four criteria, thereby representing the two best options for the risk identification of the RCB disassembly process. Rather than selecting a single methodology, the two approaches will be conjointly employed. First, a PHL provides a comprehensive and holistic list of potential hazards, which is then organized into and visualized in a logical Fault Tree.

3.6.2 Step 1 of Risk Identification: Preliminary Hazard List

To conduct the first step of the PHL analysis, it is necessary to gather all information about the system being investigated. The scope of the system is the RCB disassembly. Consequently, the RCB, the hand tool drill battery module that is disassembled, represents the major component with multiple subcomponents. This system is allocated in an environment and setting that comprises the means for the disassembly, which were determined in Chapter 3.4 and are listed in Table 4. Also, the dismantling procedure in Chapter 3.4 yields the system functions, and these are adequately examined in Chapter 4.1, and registered in Table 4 in the right column Table *3*. For the second planning step, the objective of the RCB disassembly hazard identification is determined. Accordingly, the definitions outlined in Chapter 2.1 apply and the process encompasses the stages of the now-concluded PHL planning, data acquisition, and the derivation of a hazard list.

Data Acquisition

As previously outlined in Chapter 3.4, the examined system includes the following components and fulfills the following system functions:

Table 4: List of system components (left) and system functions (right)

Manual RCB Disassembly Components	Manual RCB Disassembly Functions
- Battery Module - BMS (with resistors, transistors, capacitors, metal parts, and other printed circuit board components) - Cables - Plastic parts (hard/soft) - Metal Connectors - Screws - Human Operator	• Inspection of degree of soiling • Inspection of damage • Identification of number of screws as well as screw location • Loosening and removal of screws • Grasping battery • Separate external plastic cover • Cutting visible cables • Cutting metal connectors • Separating battery module from other internal parts

Comparing this list of system components to the energy sources hazard checklist provided by Ericson reveals that the investigated system contains charged electrical capacitors and storage batteries [45]. Furthermore, the RCB disassembly comprises general hazard sources such as current-carrying live parts, electrical shock or arc flash, inadvertent activation, explosion, fire, leakage of the battery electrolyte, structural damage to the battery, and uninsulated parts. Also, the hazard checklists provided by Rausand [56] and in the standard DIN EN ISO 12100 [57] are utilized in the proceeding step.

Development of a PHL

After obtaining the necessary data, the PHL is derived deploying the standard worksheet design for PHL. The following table structures and organizes the PHL, displaying the hazard number, the affected subcomponent as the system item, and the potential hazard and its effect (Table 5). According to the PHL instructions and Murphy's law, this list of hazards must include all possible risks, as everything that "can go wrong will go wrong". By employing approaches established by Ericson [45], Rausand [56], in conjunction with the standard ISO 12100 [57], to the investigated system of a manual RCB disassembly process, the following hazards and hazard effects can be identified:

Table 5: Preliminary Hazard List for a manual RCB disassembly

Preliminary Hazard List			
System Element Type: Manual RCB Disassembly by a Human Operator			
No.	System Item	Hazard	Hazard Effects
PHL-1	Battery Module	Direct contact of operator with inadvertently activated battery cells	Electrical shock or arc flashes, explosion, ignition of flammable substances, personnel injury
PHL-2		Battery electrolyte leakage and live parts present	Battery fire or explosion, personnel injury, inhalation of harmful gases, increased risk of cancer, chemical burns, irritation to skin and eyes, damage to health, environmental contamination

PHL-3		Exposure of battery cells to higher temperatures	Thermal runaway, battery fire or explosion, personnel injury
PHL-4		Mechanical damage to the battery cell	Short circuit, thermal runway, battery fire, or explosion
PHL-5		Undetected manufacturing defect	Increased risk of accidents
PHL-6	BMS	Direct contact of operator with live parts	Electrical shock or arc flashes, personnel injury
PHL-7		Puncture energized component	Electrical shock or arc flashes, personnel injury
PHL-8		Faulty conditions lead to operator become live through indirect contact	Electrical shock or arc flashes, personnel injury
PHL-9		Electrostatic discharge	Damage to sensitive electronics, malfunction of BMS
PHL-10	Cables	Direct contact of operator with not properly insulated wire	Electrical shock or short circuit, personnel injury
PHL-11		Operator cuts wires incautiously and punctures other parts	Short circuits, arc flashes, damage to battery cell or sensitive electrical parts
PHL-12	Human Opera-tor	Operator error in disassembly sequence	Electrical shock or arc flashes, personnel injury
PHL-13		Improper use of tools	Personnel injury
PHL-14		Using inappropriate tools	Damage to components, increased risk of electrical shock, personnel injury

PHL-15		Glare	Loss of control over actions
PHL-16		Lack of PPE'	Increased exposure, electrical shocks, short circuits, personnel injury
PHL-17		Lack of training	Increased risk of accidents, touching opposite terminals
PHL-18		Misidentification of parts	Increased risk of mistakes, damage to components, personnel injury
PHL-19		Hasty working method	Increased risk of mistakes and accidents
PHL-20	Plastic Parts	Direct contact of plastic with fluids or electrolytes	Inhalation of harmful gases, cancer, damage to health, respiratory issues
PHL-21	Metal Connec-tors	Direct contact of operator to live parts	Electrical shock or short circuit, personnel injury
PHL-22		Cutting connectors incautiously	Electrical shocks, short circuits, personnel injury
PHL-23	Screws	Inaccessibility for operator	Incautious actions, increased risk of mistakes
PHL-24		Improper handling (dropping, mishandling)	Increased risk of accidents, personnel injury
PHL-25	Environ-ment	Moisture on live parts	Electrical shock or personnel injury
PHL-26		Lack of proper ventilation	Accumulation, Inhalation of harmful gases, respiratory issues

3.6.3 Step 2 of Risk Identification: Fault Tree

To derive a logical Fault Tree based on this PHL, the top event, the critical event needs to be identified from these hazard effects. The effect that must be mitigated for a safe RCB disassembly line is personnel injury of any kind. The immediate causes of personnel injury can be categorized into four types of error: electrical error, human error, physical product error, and environmental error as illustrated in Figure 4. Now other hazard effects of Table 5 are assigned to the four categories. This yields the next level of intermediate causes for the electrical error: electrical shock, arc flashes, or explosions. Human error can be traced back to the intermediate causes of increased risk of mistakes, increased risk of accidents, and a rebound after damage to components. Similarly, within the physical product error, the causes of increased risk of mistakes and accidents can be derived from the PHL. Lastly, inhalation of harmful gases and moisture on the parts represent direct causes of environmental error. After establishing the second level of intermediate events, the third level can be created by assigning the associated hazards to the hazard effects according to the PHL. Also, before assigning a hazard in some cases it is sensible to insert a further overarching cause event which includes specified hazards out of the PHL. For example, undetected manufacturing defects but also detected physical damage can lead to increased risk of accidents and thus, to physical product damage and potential harm to the operator. The undetected manufacturing damage could be caused by faulty conditions of a component, which can be traced back to the unspecified root cause of a manufacturing error, which is represented in a diamond shape as an undeveloped event. Detected physical damage however could be observed on the battery cell or the cables. Concerning the battery cell this detected damage can be traced back to either an abraded cell can, due to a manufacturing defect, or due to age or to damaged battery terminals. The damaged cable is potentially due to not properly insulated wire or poor wire quality. Both represent basic root causes, neither requiring further investigation. Similarly, the procedure is applied to the other intermediate events and yields the Fault Tree branches visualized in Appendix B. It must be mentioned that this Fault Tree is an individual and not an exhaustive list, focusing on aspects that can be considered and addressed within the disassembly process.

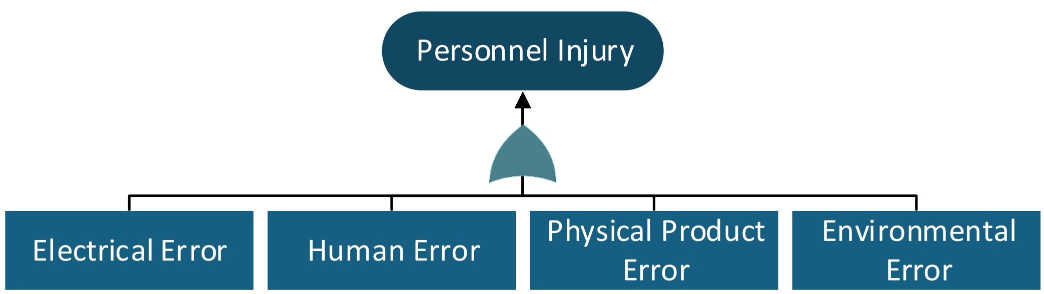

Figure 4: Fault Tree top-level event and first-level causes

3.6.4 Step 3 of Risk Identification: Shortest Paths to Failure

To identify the most significant risks based on the Fault Tree, the critical path, namely the "Shortest Path to Failure" (SPTF), is observed. The diagram indicates that the shortest path to a root cause traverses two levels of intermediate events. SPTFs occur multiple times in different areas.

In the section on electrical errors, four SPTFs are identified. Both inadvertent activation of the battery and direct contact with live parts are root causes of different intermediate events that can ultimately harm the operator. Nevertheless, all these causes can lead to personnel injury and must be avoided. In terms of human error, the undeveloped root cause of a hasty working method and the basic root causes of lack of PPE and lack of training are the three relevant root causes within the SPTFs. The hasty working method of an operator could stem from factors such as insufficient wage, personal issues, medical conditions, or competitiveness among coworkers. However, these factors are not relevant to the conceptualization of the disassembly line and are therefore not further developed. The SPTF in the physical product error branch can be traced back to the root cause of the product design not incorporating design for disassembly. Other SPTFs in this branch such as the root cause of poor wire quality or manufacturing errors incorporate one more intermediate stage and therefore, do not represent SPTF of the Fault Tree. In the environment error section, a lack of proper ventilation can cause personnel injury by inhalation of harmful gases. Additionally, the direct contact of fluids or electrolytes with plastic or electric parts can induce the formation of harmful gases and therefore, represent the second SPTF in this branch. Table 6 provides a comprehensive record of all described SPTFs with their respective branch. During the disassembly experiments, the only incident was a small spark caused by a short circuit and contact between the used tools and live parts while handling the thin metal connectors between the BMS and battery module.

This incident demonstrates that while the identified root causes do not always lead to personnel injury, the hazard is existent and not negligible. The primary risk exposure period is during the cutting of the metal connectors, which directly relates to root causes 1 and 2 of Table 6, and increases the danger of causes 3 to 5 influencing this step. Lastly, using conductive metal cutting devices like knives or cut-off grinders near battery cells, represents a period of heightened risk, despite the typical insulation on the tool handles.

Table 6: Record of all SPTF in the Fault Tree

No.	Branch	Root Cause for SPTF
1	Electric	Direct contact of operator with live parts
2	Electric	Battery is inadvertently activated
3	Human	Hasty working method
4	Human	Lack of PPE
5	Human	Lack of training
6	Product	Product design not for disassembly
7	Environment	Direct contact of parts with fluids or electrolytes
8	Environment	Lack of proper ventilation

After this elaborate risk identification, proper risk mitigation and reduction measures are developed in the concept development chapter.

CHAPTER 4: CONCEPT DEVELOPMENT

In the following chapter, a detailed concept for a disassembly guideline and environment is developed. Utilizing the acquired knowledge and information from the chapters before, the conceptualization follows the prescription of the standard in VDI 2221.

4.1 Definition of Functions

To derive an efficient working environment for RCB disassembly, the standard in VDI 2221 prescribes the determination of functions and actions that need to be fulfilled. According to the flowchart in Figure 3, the following detailed functions can be derived: inspection of degree of soiling, inspection of damage, identification of the number of screws as well as screw location, loosening and removal of screws, grasping battery, separating one external plastic cover (top or bottom), identification of internal parts, cutting visible cables, cutting metal connectors, separating battery module from other internal parts, securing the working individual from potential sparks, fires, and explosions, and a prompt reaction to sudden outbreaks. Repetitive or similar activities such as inspections are summarized into one general function. This operation consolidation results in the functions of optical inspection, screw removal, grip, separation, cut, prevention, and hazard reaction.

4.2 Search for Solution Principles

As a next step according to the standard in VDI 2221, different options to fulfill these functions, in the following called different design solutions, will be developed for the identified actions. Multiple brainstorming sessions, also with other students, were instrumental in the results.

4.2.1 Description of Solution Principles

First, for the identification process, the initial association is making use of the human eyes to detect objects. Alternatively, using optical sensors yields similar results and can be used for product and status detection and identification. For this, photoelectric sensors or laser sensors can be employed. While photoelectric sensors rely on reflection mechanisms with visible or infrared light on a low-cost basis, laser sensors emit monochromic, focused light pulses which yield a more expensive solution. Based on these reflectance properties, the position of the sensors, and the dimensions of the measuring space the object dimensions can be obtained. Other than that, a reflectance spectrophotometer provides the possibility to measure optical and reflectance properties of objects. Consequently, the combination of this device with an approach that facilitates a continuous measurement across the surface of the object can yield data that calculates the dimensions of the product and also recognizes areas of different reflectance properties, such as holes, screws, or writing. This represents another costly and complex method for optical inspection that is yet to be fully developed. Lastly, machine learning algorithms can be employed to calculate the object dimensions, properties and detect written information from an object that is recorded with a camera, specific approaches are described by Kamateros and Abdoli [58].

To perform the task of screw removal, two types of design solutions can be distinguished: destructive and non-destructive screw removal. Non-destructive methods comprise utilizing a manual screwdriver, a ratchet wrench, or a powered hand tool drill. This drill could further be equipped with more than one head to remove multiple screws at once. This multi- or single-head drill could be attached to a robot end effector and thus, represent an automated robot option for screw removal. In terms of destructive screw removal, saws could be used to cut the surrounding plastic cover until the screw falls out or can be removed.

To fix the battery in place and fulfill the grip function, human hands represent the first association for a design solution. Alternatively, a vise can be used to clamp the battery between the vise's jaws or pliers to establish a firm grip around the battery or components. Another option is to insert a battery into a cavity that possesses the negative shape of the battery model and therefore, can hold the battery in place. Lastly, a robot could be used to clamp and grip the battery or components to keep it in place while other operations are conducted on it in the meantime.

To separate parts from each other that allow for a non-destructive separation method, such as removing the battery module from the surrounding plastic external cover, four different options are presented. First, human hands can be utilized as a means for a minimal resource environment. Second, pliers help grip parts and relocate them. Gravitational force on the other hand can be used to separate parts without touching them but having them fall off or out of their original place. Rather than separating components without the application of external forces, compressed air can be utilized to dislodge them from each of their original positions using a blowout.

For the next function, cut, destructive separation methods are considered. A utility knife constitutes the first option next to wire cutters or saws. In terms of more technical design solutions, lasers can be employed to transfer amounts of energy that locally melt and thereby, disconnect components. Another option is the use of water jets, which are formed by focusing and pressurizing water jets into which abrasive, cutting material such as specific sand, is added.

Preventative measures for the RCB disassembly process must target the root causes identified in Chapter 3.6.4 and listed in Table 6. For example, incorporating a “glovebox” which is comparable to a sandblast cabinet or a hot cell in the nuclear industry. This cabinet can be observed through windows or be completely transparent acrylic plastic, includes a pair of gloves to reach through into the box center and parts can be inserted through lockable doors. This concept shows the advantage of creating an enclosed space for the RCB disassembly and its hazards, without direct contact of the operator to live parts. Furthermore, according to Kirchner, the glovebox represents an indirect safety technology as it serves as a safety device that physically separates the operator from a hazard [59]. Therefore, it addresses the SPTFs of direct contact to live parts (No. 1), it provides a physical separation in the event of No. 2

(inadvertent battery activation) and addresses No. 4, the lack of PPE. Regarding the environmental SPTF, it provides an enclosed space in which the operator is shielded from the root causes No. 7 and No. 8. Alternatively, ultrasonic testing can be utilized as a preventative method. Firstly, an ultrasonic scan can identify cracks, damages, or internal defects of battery cells which increase the risk of electrical shocks or explosions as obtained through the Preliminary Hazard List and the Fault Tree [60]. Secondly, ultrasound can detect the formation of dendrites which enhance short circuits and other electrical issues [61]. During charging or discharging cycles ultrasonic testing can monitor and measure temperature changes which can lead to critical hazardous events before they occur [60]. Thirdly, this technique has the benefit of non-invasiveness and no damage to the battery while monitoring and detecting battery properties. In conclusion, ultrasonic scanning addresses SPTF No. 2, to detect internal damages before possibly causing inadvertent battery activation, as well as provides information to avoid No. 7, direct contact of parts with fluids or electrolytes. The next option is a full discharge of the battery pack to minimize the risk of electrical issues by setting the state of charge to as close to zero as possible. However, it cannot be guaranteed that there is no residual charge left in the battery and hence, still represents a non-negligible, but reduced risk. A successful full discharge mitigates SPTF No. 1 and No. 2, the electrical SPTF. Another option is a fail-safe structure which follows the methodology to require a signal or electricity to be not triggered and a lack of the signal causes the fail-safe structure to be activated. For example, a button could be pressed by the foot of an operator to separate two metal, hollow halves of a box, and in case of a spark or fire, the foot is removed by the operator leaving the workstation, the signal is interrupted, and the two halves of the box encapsulate the hazardous situation. This has the effect that fire outbreaks can be smothered, and the hazardous space is enclosed and separated from the operator. Such a fail-safe box structure does not protect the operator from root cause No. 1, direct contact with live parts. In case of a progression of this SPTF, the hazardous components are meant to be enclosed before reaching upper levels of the Fault Tree such as personnel injury. The same applies to the root causes No. 2, No. 7, and No. 8, since they are not directly avoided but the operator is physically shielded and protected at a stage of the hazard progression which depends on the operator's reaction time when the signal is interrupted. Lastly, another preventative approach is to adapt the humidity around the RCB disassembly as the relative humidity shows a clear relation to fire burning conditions [62]. Establishing a higher relative humidity level in an enclosed space, like a workstation box, in which fire is less likely to burn well, can serve as a method to monitor humidity conditions and prevent fire outbreaks [63]. This prevention design solution does not eliminate the risks or SPTF; however, it establishes a threshold for root causes to progress until they are hindered or stopped by this adapted humidity, preventing personnel injury. In the event of an explosion, the humidity can reduce the scope and size of the fire but does not guarantee the absence of any explosions. Therefore, it mainly addresses the courses of SPTF No. 1 and No. 2.

For the last function of hazard reaction, the first association yields using fire extinguishers manually in case of an outbreak. Another option is to attach fire agents around the workstation, which can be triggered by an accessible or automated signal. This reduces the dependency of the fire extinguishing success rate on the human capability to target the fire, as the attached agents could be designed and arranged in such a way to ideally hit the area of the workstation. Smothering represents a commonly used alternative, for which nitrogen purging or carbon dioxide flooding illustrate two different options. However, this approach shall not be used in spaces in which human operators are still present due to potential breathing issues and threats to health and life. Lastly, fire can be smothered by solid materials, such as sand. In the case of medium-sized fires, the sand serves as a burn-out ground. Conversely, according to Buchmann, the founder of the Battery University, in the instance of the first spark and initial moments of a fire outbreak, sand can be employed to cover and extinguish the flames of LIBs [64].

To reduce the identified risks and mitigate the SPTF some further risk reduction measurements are developed. To prevent the direct contact of the operator with live parts and to avoid consequences due to a lack of PPE, rubber gloves represent another physical method of operator insulation and address SPTF No. 1, No. 2, and No. 4. Respiratory PPE such as dust masks or full-face respirators can be utilized to target specifically SPTF No. 7 and partially No. 4, not No. 8 as the latter refers to the lack of proper ventilation which should prevent moisture from reaching live parts. Anti-static mats on the other side can be utilized to support the discharge capacity of static charge of the components by being placed on the working surface or support the discharge capacity of the operator footwear by being placed at the operator position to facilitate the dissipation of static charge from the operator's body. To target SPTF No. 1 and No. 2, these mats require a connection to an earthing point or earthing plug, which cannot be ensured in environments with minimal resources. Similarly, earthing wristbands establish a direct conductive connection to dissipate the charge to the ground and protect the operator, encompassing electrostatic discharge. In combination with rubber gloves, wristbands must be worn underneath. It is designated to address the same SPTF courses, which are typically employed to safeguard electric components, rather than only the operator. Furthermore, the wristbands must be connected to an earthing point and can be utilized in conjunction with anti-static mats. The SPTF No. 3 and No. 5 are human errors that can be addressed with proper training, information, and education as well as by employing error-proof development methods. These encompass anti-symmetrical shapes, fixtures, and tools to facilitate clear, unmistakable orientation and a single, unambiguous operation possibility for each step. Furthermore, to reduce the possibility of human error, steps can be carried out automatically, and decisions can be made using predefined algorithms. This approach avoids the potential for interpretation space and ensures that the human operator cannot misinterpret or mistake the automatically determined result. Such measures to avoid human error can also serve to decelerate the operation speed to mitigate hasty working methods. However, this negatively impacts the realizable disassembly cycle time and must therefore be carefully considered. Lastly, SPTF No. 6 cannot be addressed by the disassembly sequence because the product design is only determined by manufacturers and legislative and regulatory institutions. For the SOH assessment which is integrated into the concept a more elaborate description of different design solutions is given in the following chapter.

4.2.2 Integration of SOH Assessment

In this subsection, the added value of information on the SOH of an EOL-RCB as well as a meaningful approach to utilize the results of an SOH assessment in a manual RCB disassembly line are examined.

Added Value through SOH Assessment

The major factors influencing the battery SOH, such as physical or chemical damage but also performance degradation are due to aging in time or due to the number of charging and discharging cycles [20,21]. Parameters that show a representative, accurate relation to aging can be used to evaluate the SOH of a battery. However, it must be noted, that the SOH is related to the aging and safety condition of the battery but capacity change is not always the reason for battery degradation [65]. It must be ensured that the measurements are conducted under similar conditions, as particularly battery properties such as voltage, capacity, and resistance are highly temperature dependent. Therefore, it is important to pursue equal measurement conditions in order to ensure the repeatability of the measurements and reliability. Furthermore, all methods employ different abstract models to simplify the complex internal battery processes: the greater the level of abstraction, the more inaccurate and unrepresentative the resulting values. Thus, utilizing data such as the maximum recommended current for the respective battery type from the original battery datasheets allows for more confidence in the resulting SOH values. Further insights on the correlations of battery properties and their effect on the battery condition can be found in the work by Michelini et al. [65].

Target Categories of SOH Assessment

To meaningfully utilize this information about the battery, the targeted classifications of the battery cell are determined to enable further treatment of the battery cell and thereby extend the lifespan of some batteries rather than landfilling or recycling all of them. The basis to categorize the battery cell into reuse, repurpose, remanufacture, refurbish, repair, or if necessary, recycle according to Potting et al. is going to refer to the result of the SOH assessment [15]. According to Potting et al., reuse is the optimal strategy for extending the lifespan of systems and their components [15]. Consequently, the objective of reuse can be achieved if a RCB test is allocated upstream of the disassembly. This pre-test must yield a first, low effort, and quickly obtainable representative value of the battery performance condition. However, prior to the disassembly, no sufficiently representative value can be measured to ensure adequate reusability. Voltage, for example, does not represent any internal chemical or electrical developments of the RCBs, and a decision for advisable reusability solely based on voltage is neither accurate nor reliable. Thus, the reuse category is not targeted within this disassembly line. Another option, typically not including disassembly and reassembly, is refurbishing which entails the modernization and upgrading of a product or easily accessible parts and hence, is not considered either [15]. Nonetheless, a pre-test supports the filtering of working EOL-RCBs, as a measurement of no voltage sorts out defective EOL-RCBs and avoids needless disassembly and effort. Repair is a potential category for batteries that do not provide any charge in the pre-test or later for batteries whose SOH cannot be assessed due to potential internal defects. It resembles the maintenance and replacement of parts if necessary to restore the product's original functionality [66]. This could be the case if a part of the battery cell such as the surrounding case, electrodes, or internal separators, is defective and can be repaired to restore the battery’s functionality. It is important to acknowledge that a lack of functionality is not always remediable by a successful repair but can be irreparable. The detection of the defect, which requires the use of specialized equipment the involvement of trained personnel, and typically a disassembly, can also be expensive and pose hazards identified in the PHL (see Table 5). Consequently, in order to avoid extensive costs and minimize the exposure to avoidable risks, the repair option is excluded from the subsequent stages of this research. Another option is repurposing the battery which refers to the usage of a battery as something other than an electricity storage, for example as a structural building component. However, batteries which contain hazardous substances are not to be used in other applications, and to mitigate this danger the option of repurposing is not further considered. The EOL-RCBs discarded at any stage are assigned to the lower bound category **recycling**, the useful application of material, which is visualized in Figure 5.

All batteries which do yield a voltage measurement, are subject to dismantlement and a SOH assessment. After a product disassembly, the most desirable classification is remanufacturing, as parts, and batteries, in good condition can still be utilized as stationary electricity storage [67]. The target is that the remanufactured item achieves the same quality standard as a new product or at least 90 % of the initial battery capacity according to the European Union [67,68]. This process typically includes the disassembly of the discarded product [66]. Batteries with exceptionally to sufficiently good SOH results can be remanufactured for the same application, which in this case is hand tool drill batteries. Many works of literature such as research by Tan et al., recommend removing a battery pack once a battery cell shows a SOH value below 80 % [69]. A study by Tran et al., however, found that extending the operation time until a SOH threshold value of 70 % doubles the amount of possible charging and discharging cycles of investigated LIB cells [68]. This 70 % represents a current orientation value for a lower threshold until which batteries can be used for electricity storage, although it may change in the future.

Also, it needs to be considered whether cells are evaluated individually, or an assessment of the entire battery module is performed. It is notable, that in flat battery modules, cells situated in the middle are exposed to more heat radiation, being enclosed by border cells, which, in contrast, have a greater surface available for cooling. This variation in heat exposure can have disparate effects on the temperature-induced aging of cells. However, the research by Tran et al. indicated that the replacement of an entire battery module yielded 1 - 3 % fewer charging cycles than the best outcome of single-cell replacements [68]. Thus, due to this negligible amount, the difference in achievable cycles will not be decisive, and the choice of a battery module or cell evaluation is still subject to further research. In the event of not sufficiently good SOH values, but higher than the identified lower electricity storage applications threshold, the batteries can be used in applications which require lower capacities. For this SOH value range, it is important to choose utilization options that accept and are compatible with lower battery capacity rates. Such products can be smaller household devices like electric toothbrushes, flash-lights, or power banks. As this utilization still refers to the electricity storage and supply function of batteries, it is considered as remanufacturing [15].

Furthermore, two subsequent stages of an SOH assessment after the pre-test provide additional value. Employing a first SOH evaluation method which yields a first rough impression of the SOH value in little time can identify the upper bound of batteries with exceptionally good SOH values and the lower bound of below critical SOH threshold values. Batteries with values designated to these two types are categorized for high-quality remanufacturing or recycling respectively. Batteries on which values in between are measured can progress to a second SOH evaluation technique, which possesses higher accuracy, provides a more precise representation of the internal battery condition, and can be more time intensive. This higher precision leads to a refinement of SOH values in the middle ground and beneficial additional accuracy for the classification into future products, the batteries are remanufactured in. The exact development of this two-stage SOH assessment requires more exploration which exceeds the scope and focus of this master's thesis.

To assign currently valid quantitative values to the SOH target categories, the aforementioned critical lower SOH threshold of 70 % according to Tran et al. [68] is utilized. When the SOH of a battery cell is below 70 %, the battery cell is discarded and categorized for **recycling.** This also occurs if the pre-test does not yield a voltage measurement. Between 70 % and the typical 80 % SOH according to Tan et al. [69] is a region in which the deliverable capacity is noticeably reduced and therefore, the batteries shall be remanufactured for a lower capacity purpose [67]. For the remaining upper bound between 80 – 100 % SOH, the battery is categorized for same purpose remanufacturing. Figure 5 illustrates the categories into which the SOH assessment classifies the batteries, intending to supplement the dismantling sequence with subsequent utilization recommendations.

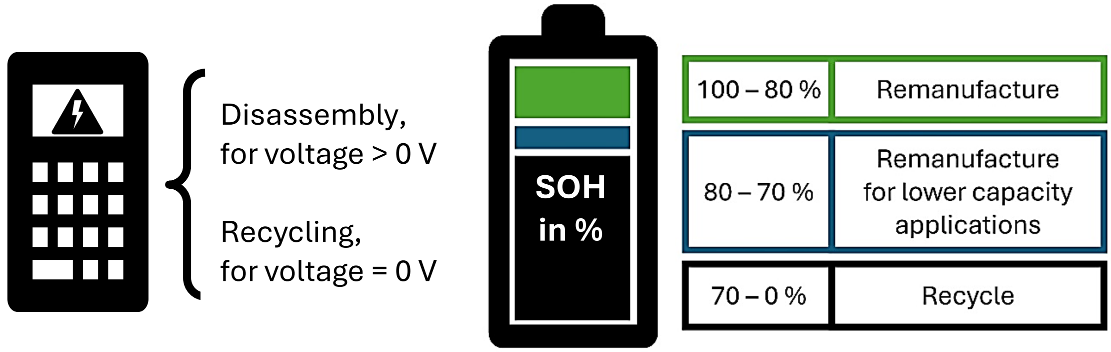

Figure 5: Targeted treatment categories for the battery cells dependent on the pre-test and the SOH assessment (left: pre-test target categories, right: post-disassembly SOH assessment target categories)

Selected methods to perform the SOH assessment (i.e. Coulomb Counting, Capacity Measurement, Two Pulse Load Test) are briefly described in Appendix C and extended descriptions can be found in the works of Berecibar et al. [21], Coleman et al. [70], Pradhan and Chakraborty [22] or Zuluaga et al. [71].

To perform the pre-test, independently of the SOH evaluation, different design solutions can be considered. A multimeter represents the inexpensive, quick, conventional way to measure battery voltage. However, the correct usage and attachment of the probes to the battery under investigation as well as the correct interpretation of the given value open many human error possibilities. Another option is a Data Acquisition (DAQ) System, which incorporates similar functionalities to the multimeter, but without a plain graphical user interface. To mitigate human error, the system can be further developed with error-proofing mechanisms, and the final decision-making process automated by the system rather than the operator. While this approach requires additional development and financial investment, it promises a lower error rate and fewer misassigned items. Another option is to design the DAQ system with a fixture to process and measure batches of batteries simultaneously. This method shortens processing times but necessitates a model-specific design. The fixture must be tailored to ensure direct contact with the positive and negative terminals, which vary in location depending on the battery model. Lastly, using an oscilloscope for pre-testing can assess battery operability by measuring voltage. As the oscilloscope can measure various properties over time, it is an expensive technique, decreasing its feasibility in a minimal-resource workstation. A comparison of these techniques based on relevant criteria for the RCB disassembly process is provided in Chapter 4.4.

4.2.3 Visualization in a Morphological Box

In a subsequent step, all solution principles for each identified function and the pre-test are collected in a comprehensive visualization, a morphological box, as illustrated in Figure 7. The supplementary risk mitigation measures are not listed in the morphological box, as they can be utilized in conjunction with each other as additional measures. Since the morphological box identifies one solution principle for each function the integration of these supplementary measures is not appropriate. Furthermore, the determination of one distinct SOH assessment method plays a subordinate role in disassembly, which is why they are not included in the morphological box either.

4.3 Derivation of Potential Manual RCB Disassembly Concepts

According to the standard VDI 2221, four different concepts are developed from this morphological box by connecting one design solution for each function and thus, creating one possible concept.

Concept 1 –minimal resources

The first selection objective is to minimize equipment and investment costs, promoting a minimal resource environment. Consequently, tasks that can be performed using only human senses and activities are preferred: the human eye for optical inspection and human hands for gripping and separation tasks. Additionally, manual tools such as screwdrivers, utility knives, and sand are the most cost-effective design options for their respective functions. In the prevention section, identifying the least expensive option is more complex. Nonetheless, ultrasonic testing, fail-safe structures, and variable workstation humidity all necessitate a higher level of equipment. The glovebox and the full discharge option both require comparatively less equipment. For this first, least expensive version for a minimal resource environment, the choice is the glovebox, which requires a modest one-time investment but no operational costs as it does not require a power supply. This ensures the prevention function in the process and is not dependent on operator knowledge, skills, or training in comparison to the full discharge design solution. Lastly, for the pre-test, the multimeter is preferred over the other options in terms of initial investment and operational cost and is therefore selected for concept 1.

Concept 2 – innovative structural solutions

For the next path through the morphological box, the objective is to create an innovative concept regardless of costs, with an emphasis on human safety, process time, and ergonomics, by incorporating original structural design solutions. Excessively resource-intense solutions are not regarded in this concept as the focus is on innovative structural workstation design. A reduction of the processing time profits from semi-automated operations such as utilizing a photoelectric sensor to detect objects to fulfill the optical inspection. The utilization of hand tool drills with more than one head facilitates the removal of multiple screws at once. A fixture specifically for the processed battery type by providing a cavity shaped like the negative of the battery, serves for the grip function. To enhance human ergonomics, pliers are utilized for separation, which allows for less force to achieve the same result, and wire cutters are employed for cutting operations. Laser cutters and water jets are not considered due to their resource-intensive operation. As for risk prevention, the fail-safe structure, two halves of a box encapsulating the hazardous situation once triggered, represents an innovative solution. A concept that can trigger a protective reaction in- or dependent on the operator's decision or decision time. In terms of a prompt hazard reaction solution principle, a structural arrangement of fire agents around the workplace is chosen. For the battery pre-test, the selected solution is the employment of a DAQ system, with a tailored fixture for a battery batch to prevent human error and reduce the process complexity for the operator. Not only the voltage but other properties can be measured and integrated into the machine-generated decision.

Concept 3 – automated

As for the third concept design solutions are selected when they facilitate the objective of an automated process optimized for least human action. Hence, an application of machine learning algorithms shows the benefits of implementing additional battery models for recognition and adapting the disassembly process according to the recognized model. In an automated process, robots take over the tasks of screw removal and grip. Pliers and laser cutters display further tools that could be attached to a robot or taken over by a machine. In this automated process the percentage of electrically conductive parts, such as robot end effectors, arms, or constructions, is increased in comparison to the previous concepts. Accordingly, a full discharge can be performed on multiple batteries at once and it is chosen to prevent any damage and breakdown of machinery in case of a fire outbreak. Similarly to the ideal concept, smothering like nitrogen purging presents the choice of the quickest and most effective hazard reaction, particularly in spaces without human operators. For the battery pre-test, however, the voltage measurement could be entirely automated by utilizing a single battery fixture and DAQ system. A potential process is to insert one battery at a time into the measurement arrangement, measure it, and have it either fall out of the fixture or be pushed onto a conveyor by a piston while the robot arm gets the next battery pack to insert it into the fixture.

Concept 4 – compromise

With an objective to develop a sustainable and viable concept for a manual RCB disassembly process, that adapts, and improves, current disassembly processes, a middle ground combining concept 1 and concept 2 is considered. This combination of cheap methods and selected innovative approaches yields a minimal resource, safe, and original disassembly process. Therefore, with respect to the Preliminary Hazards List and the Fault Tree, the steps of optical inspection, grip, and separation are negligible tasks in terms of the exposed risks and are conducted as discussed in the inexpensive concept. However, the use of an electric hand tool drill represents the middle ground between the manual screwdrivers and the hand tool drill with multiple heads and is chosen for this concept. Additionally, the wire cutter is a safe choice for the separation task with additional insulated handles and design which enables proper, safer usage in comparison to a utility knife. To add physical means to break the link and conduct a connection between the operator and battery the glovebox is selected as a preventative measure. For the fulfillment of the hazard reaction sand is chosen as an inexpensive, easy-to-implement, and sustainable way for a prompt hazard reaction. The last function is determined by the least complexity, required time, and implementation cost. Consequently, the decision is to proceed with a multimeter for the battery pre-test. This design module completes concept 4 by finding a middle ground between innovative approaches and inexpensive, realistically realizable decisions.

The following Figure 6 serves as a legend and assigns each of the described models a color which is utilized to mark the different paths within the morphological box in Figure 7.

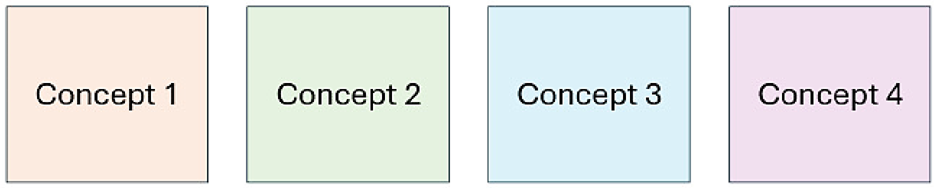

Figure 6: Assignment of colors for each concept

Function \ Design solution	1	2	3	4	5	6
Optical Inspection	Human eyes	Camera and machine learning	Photoelectric sensors	Laser sensors	Reflectance spectrophoto meter	
Screw Removal	Manual screwdriver	Ratchet wrench	Hand tool drill	Hand tool drill with multiple heads	Saw	Robot
Grip	Human hands	Bench vise	Pliers	Robot	Fixture with negative cavity of the battery	
Separation	Human hands	Pliers	Gravitational force g	Compressed air		
Cut	Utility knife	Saw	Wire cutter	Water jet	Laser cutter	
Prevention	Glovebox	Ultrasonic testing	Full discharge	Fail safe box structure	Higher humidity	
Hazard Reaction	Fire extinguisher	Fire agents around work station	Smothering	Sand		
RCB Pre-Test	Multimeter	Data Acquisition System (single RCB)	Data Acquisition System (many RCBs)	Oscilloscope		

Auxiliary prevention measures	Respiratory PPE	Anti-static Mat	Grounded wristband	Rubber gloves	Rubber insulation sheets	Grounded workstation

Figure 7: Morphological box displaying design solutions to fulfill identified manual RCB disassembly functions with concept paths and additional auxiliary prevention measures

4.4 Evaluation and Selection of Disassembly Concept

The main consideration point for the concept selection is the optimal fit to the overall objective of this research; the conceptualization of a safe, manual RCB disassembly line. For a justified selection of the disassembly concept, decision criteria are gathered. It is important to consider the criteria of all three sections of the project management triangle: cost, quality, and time. In regard to costs, the target is to address and improve the outlined current state of the use case in Chapter 2.3 and thus, implement the selected concept with **minimal resources** and minimal infrastructure, such as a power supply. This leads to the assumption that concept 1 should be selected because it requires the least amount of cost and equipment. However, other criteria must also be contemplated. Next to the infrastructure, the set-up efforts respecting **initial investment costs** are regarded. In case the technology is to be developed for or tailored to this RCB disassembly, such as a fail-safe structure or a higher humidity environment, the concept is evaluated differently from existent design solutions due to an increased **development time**. Another time consideration is the **calibration time, which reflects** the need for calibration of all technical systems before operation and their accuracy must be ensured. This applies to the investigated optical inspection technologies, the cut and prevention function as well as robot applications in any field. Similar to the calibration time is the expected maintenance time and frequency of a design solution. As these two aspects are closely related and almost refer to the same product, they are summarized in the criterion calibration time. Furthermore, options which are not only time intensive during the setup but also increased **operation** times are less favored, such as those associated with the manual screwdriver for the screw removal or the vise to fulfill the grip function. Apart from time-focused criteria, the knowledge or operator training requirement due to the level of operation complexity is considered as the level of **process simplicity and intuitiveness**. This criterion can be considered a cost consideration, but in this case, it is considered a quality criterion, as the result of the disassembly step is dependent on the knowledge level and expertise. Another quality aspect is the **flexibility** of a process regarding adaptations due to future changes in the product structure and shape, quantitative thresholds, or technology. In this case, specifically, a certain level of flexibility is essential due to the different structures of the investigated five different battery types. Lastly, the **SPTF risk mitigation** is assessed as another quality-related criterion.

The identified SPTF root causes are evaluated to determine the extent to which they are addressed and mitigated by the concepts. This evaluation utilizes nine criteria, assessed on a five-point Likert scale: (++ for high satisfaction, - - for strong dissatisfaction, and -, +, o for varying levels of satisfaction). In practical application, criteria such as low resource usage and high process simplicity are prioritized, each assigned a weight (W) of two. SPTF risk mitigation, crucial to the overall objective, carries a weight of more than three and cannot be outweighed by fully satisfactory criteria sections such as time or cost alone. For instance, achieving satisfaction in the cost section results in an overall score of four, considering the weight of two assigned to the low resource criterion. The SPTF risk mitigation criterion is assigned a weight (W) of five to ensure its significant impact. Numerical scores are calculated based on assigned values: -1 for minus, +1 for plus, 0 for neutral, and double values for double signs. The concept comparison as well as the resulting assigned values are recorded in Table 7, while more details are provided in Appendix D.

Table 7: Concept comparison and justified selection employing a Likert scale

Criterion \ Concept	W	Concept 1 minimal resource	Concept 2 innova-tive	Concept 3 auto-mated	Concept 4 middle ground
Cost					
Low resource costs	2	+	-	-	O
Low initial investment costs	1	+	-	- -	O
Low operation costs	1	+	O	-	+
Time					
Short development time	1	+	- -	O	+
Short calibration time	1	++	-	- -	++
Short operation time	1	- -	+	++	+
Quality					
High process simplicity	2	O	++	+	+
High process flexibility	1	+	- -	-	+
High SPTF Risk mitigation	5	+	+	++	+
Sum		11	2	6	13

Consequently, concept 4 yields the highest value regarding the considered decision criteria and assigned weights. Therefore, it represents the best concept for a safe, manual disassembly line and is detailed in the following chapters.

As one of many stages within the RCB disassembly line, the SOH evaluation does not represent the core element, but it serves to provide valuable indicative information on further utilization possibilities of the battery. Therefore, the selection of the SOH method is also done with selection criteria which depend on the level of complexity and the equipment cost. This secondary decision utilizes a 0/1 rating, reflecting its appropriateness for the RCB disassembly process. For both values, a high estimation yields a 0, whereas a low complexity and low-cost option are assigned a 1 in comparison, as shown in Table 8. However, the accuracy of the SOH evaluation is assessed at a value of 1 in the event of higher expected accuracy and a 0 for lower accuracy and precision of the method. Lastly, the RCB disassembly line can be regarded as a process line which means that the process time is a critical property. Hence, for a quick estimation of the SOH value, a value of 1 is assigned and methods that require long calibration, configuration, and measurement times are designated a 0. The criteria of accuracy and complexity can be assigned to the quality property, which forms the vital characteristics of the project management triangle in conjunction with cost and time. By assigning weights and adding the resulting products of weight and respective values to each other, each method yields a final score. This score represents the sensible applicability of the method for the examined process. In the event of a two-stage SOH assessment, as outlined in Chapter 4.2.2, different weights according to the respective SOH evaluation stage can be assigned. The investigated SOH assessment methods are evaluated in the examined criteria as recorded in Table 8.

Table 8: Comparison of SOH assessment methods

Method	Accuracy	Complexity	Cost	Time
Coulomb Counting	0	1	1	0
Capacity Measurement	0	1	1	1
Two Pulse Load Test	1	0	0	1
Electrochemical Impedance Spectroscopy	1	0	0	0

For the following procedure, a two-stage concept is considered. The first, rough estimation requires minimal time, little cost, and little complexity, which results in a weight W of two for these three criteria. Consequently, the Capacity Measurement yields the best fit with a result of 6. For the second stage, accuracy is the most important aspect and more significant than a satisfactory evaluation of all other three criteria. For this reason, accuracy is assigned a weight W of 4 and this yields the Two Pulse Load Test to represent the best SOH second stage precise measurement technique.

4.5 Formulation of a Coherent Concept

In this section, concept 4 is detailed regarding an appropriate workstation arrangement, the different function modules, and the necessary tools.

4.5.1 Definitions of Workstations

The selected design solutions are summarized as human eyes, human hands, a hand tool drill, a wire cutter, a glovebox, sand as a hazard reaction, and a multimeter for the pre-test. By employing a backwards-directed approach, the battery disposition triage and therefore necessary SOH assessment requires one properly equipped station which can be regarded as being separate from the other disassembly stations. The last few steps of the flowchart; all functions that must be carried out in the glovebox due to potential risks as identified in Table 5, are listed next. Thus, the functions of physically separating internal components from the battery module as well as cutting connectors and cables must be performed in the glovebox. As the cut of metal connectors represents the step in which direct contact with live parts or the inadvertent activation of the battery can occur, the selected hazard reaction substance, sand, must also be allocated in the glovebox. The grip function is fulfilled both in and outside the box. Tracing the process flowchart in Figure 3 further up leads to the removal of the external covers which is possible both inside and outside the glovebox. Upon further examination of the flowchart, it can be observed that the removal of screws comes before the removal of the external covers. This initiates the idea of a function and location separation to perform the screw and external cover removal at one workplace and then insert the remaining components into the glovebox, the subsequent workstation. Another argument for this split is to minimize the amount of metal components, such as removed screws, within the box which could accidentally contact battery terminals or other live parts. Before the screw removal, an optical inspection must be implemented as well as the battery pre-test. To raise the efficiency of the operators, facilitating the concentration on only two or three tasks enhances productivity, which is why the pre-test of the battery, and the screw removal are divided between two distinct workstations, next to the glovebox station. Additionally, this distribution and specialization of operators reduce the risk of faults, which this way do not immediately affect other stations, thereby increasing the error resistance and process stability. Furthermore, this approach has the additional benefit of incorporating only one major device per workstation: a multimeter, hand tool drill, wire cutter within the glovebox, and SOH assessment equipment. Consequently, workstation 1 performs the battery pre-test and optical identification of external damages and more whereas workstation 2 fulfills the task to remove screws. As the Ryobi model has internal screws as well, for this model the approach of function separation is chosen. In conclusion, after removing the external covers and loose parts within the glovebox as well as cutting cables and metal connectors, an optical damage detection of the Ryobi model follows next. In the event of no detected damage to the battery cell module or BMS, this module is handed back outside the box to workstation 2. Here, at workstation 2, the three internal screws attaching the BMS to the battery module and two screws holding the frame together are removed. The frame and the BMS are sorted into discarded plastic and electronics repositories respectively. By opening a sliding door from the inside and positioning the extracted battery outside, right next to the glovebox in designated spots for either recycling or further processing, the battery modules are transferred to workstation 4, SOH assessment and categorization. This back loop has the disadvantage of potentially not detecting battery defects in workstation 3 and exposing workstation 2 to the risks. However, it involves the advantage of limiting the operation complexity of workstation 3 to only cutting, separating, and gripping tasks and keeps the task of screw removal to its respective station. The reduced number of tools enhances productivity and by enabling operator specialization, improves efficiency. As a matter of course, these workstations are allocated in the order of first battery pre-testing and optical inspection, then screw removal, and then further disassembly in the glovebox, and lastly, SOH evaluation and battery categorization. Each workstation is assigned a number between one to four, which represents its position in the manual RCB disassembly process flow. This sequence as well as the respective functions are depicted in Figure 8.

4.5.2 Detailing of Execution and Equipment Requirements

In terms of tools, the main devices multimeter, hand tool drill, glovebox, and SOH equipment represent the key items in their respective workstations. However, more detailed considerations are necessary for a successful RCB disassembly. Workstation 1 utilizes the multimeter, the batteries of which must be replaced or recharged at some point in time. Thus, batteries that are used in the device need to be provided in long-term estimations. Also, sufficient lighting conditions are necessary to successfully perform the optical inspection.

Workstation 2 requires a hand tool drill with a charger and thus access to a power outlet at some point in time. Next to that, a TR10 bit and a cross-recess, Phillips, bit in size 0 and size 1 as well as a slim drill bit extension for the Ryobi model (see Chapter 3.3) must be provided. Workstation 3 necessitates the glovebox with attached rubber gloves which serve as PPE and a wire cutter within the box. In terms of the box, there are metal and acrylic boxes available. Metal gloveboxes are commonly used as sandblast cabinets and therefore cheaper and easier to acquire. However, to prevent the occurrence of electrical issues such as electrical shocks if contact with the metal box is established, metal gloveboxes must be completely lined with rubber on the exterior. Interior rubber lining additionally prevents short circuits. Furthermore, to protect the operator, metal gloveboxes must be properly grounded to allow a safe discharge of the currents. On the other hand, acrylic gloveboxes, which have reduced risks of short circuits and electrical issues, are extremely expensive. However, for the use of plastic boxes, it is still recommended to ground the box and utilize a grounded wristband to mitigate the impacts of potential electrostatic discharges. Lastly, a glovebox can be built out of wood or particle board which is inexpensively available in most countries. This self-built option can be tailored to the disassembly process by providing different channels for different battery components and battery conditions. Yet, this box also must be grounded. Thus, depending on the choice or availability of gloveboxes, additional equipment must be acquired. Regardless of the type of box, each must be supplemented by at least three repositories, for plastic, electronic waste, and damaged, discarded batteries as well as sand storage. In the following, a self-made chipboard glovebox is selected, and a first draft is designed in Appendix E. Workstation 4 includes exposed battery modules that require the operator to wear insulating rubber gloves. Also, this station requires the selected SOH assessment equipment and three different repositories for the target categories as derived in Chapter 4.2.2. To facilitate an ergonomic process, the workstations shall be allocated on countertop height, allowing for both standing and sitting operations.

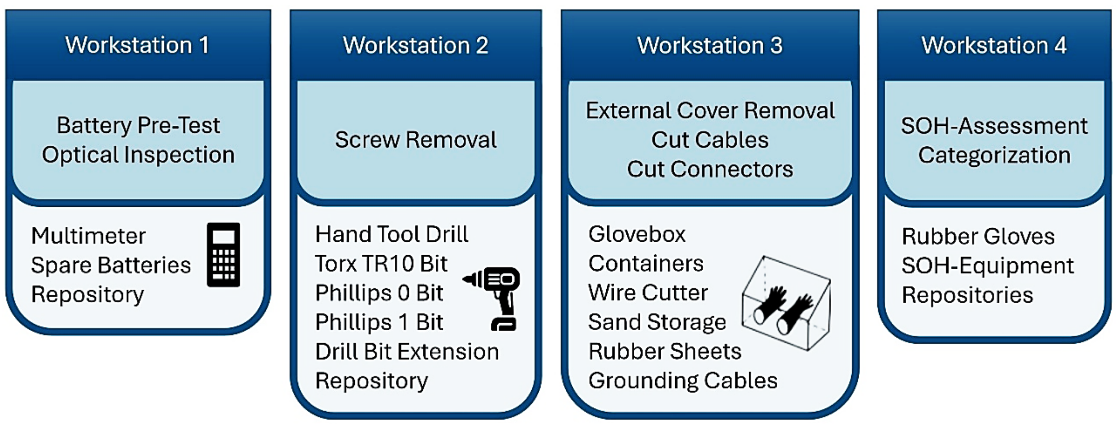

Figure 8: Workstations of the manual, safe RCB disassembly line with respective tasks and necessary equipment

With the derivation and design of these four workstations to conduct a safe, manual disassembly of EOL-RCBs, the conceptualization and development phase is now completed. Following the development of the process flowchart in Figure 3, the elaborate risk identification in Chapter 3.6, and the deduction of corresponding risk measures, the objective of this master’s thesis has been achieved and will be discussed in the following chapter.

CHAPTER 5: DISCUSSION

After the development of the RCB disassembly workstations, this chapter briefly summarizes the results and then evaluates the final concept with respect to the mitigation of identified hazards, the feasibility in practical applications, and limitations to the concept and the research itself. Additionally, the automation potentials of the selected concept are outlined and final responses to the investigated research questions are given.

5.1 Summary of the Safe, Manual RCB Disassembly Process Concept

Acquiring an EOL-RCB sets the initial conditions. Immediately following this, the multimeter at workstation 1 is configured for voltage measurement. After ensuring the RCB temperature is approximately at room temperature, the pre-test is conducted. Otherwise, the RCB is set aside until it is at room temperature. Attaching the typically red probe to the positive terminal and the black probe to the negative terminal of the RCB represents the next steps. This connection must be maintained until the multimeter has settled on a value. During this period, the battery pack is subject to an optical inspection to identify any external damage. If a critical dent or deep rupture down to battery cell level is detected, or the multimeter value reads zero volts, the battery is discarded into the recycling repository. In case it is undamaged the battery is transferred to workstation 2. Here, the external screws of the battery pack are loosened and removed with a hand tool drill. If no screws are detected, other non-destructively detachable connections are searched for, such as clips or bolts, and loosened. In the event of Makita1 or similar models, on which no non-destructively detachable connections are found, the battery is discarded in the recycling repository. Once all attachments are loosened and screws are extracted from the hard plastic covers, the battery is placed in the designated location to indicate its readiness for workstation 3. The battery is moved into the glovebox through the opening of a sliding door from within, thus ensuring that only one battery is processed at a time, reducing fire and explosion propagation potential. The glovebox serves as the main risk-reducing measure by physically separating the operator from hazardous components during high-risk processes. In the glovebox, the external covers are removed with the use of rubber gloves to expose the internal battery pack components. After a first visual inspection, the wire cutter is employed to cut all cables and metal connectors. During this step, the glovebox protects the operator if the battery is inadvertently activated, if harmful gases form due to an exposure of electrolytes, which harm the operator when inhaled, or that the operator experiences direct contact with live parts without PPE. This approach addresses most of the identified SPTFs. In case a spark is ignited, sand from a small sand depot can be grabbed and used to cover the affected spot. If the spark directly ignites other components and ignites a fire which can cause the battery cell to explode, the battery pack must be thrown into the sand storage and the hands removed from the glovebox. If no electrical hazard is encountered, the separated parts are pushed into different channels into containers. These containers are intended for electrical components such as a BMS unit or the capacitor from DEWALT and for plastic parts. In the event a damage is detected on the battery, a discarded batteries channel is provided for recycling. In the case of a Ryobi battery, the battery is displayed on a "back to workstation 2" location outside the insertion door, where the battery can be picked up to have the internal screws removed. All extracted undamaged battery modules are transferred to workstation 4. At workstation 4, the SOH assessment of different batteries is conducted under comparable thermal circumstances to ensure consistent testing conditions and the reliability of the measurements and resulting calculations. The obtained information on the internal processes and conditions indicates in which one of the three possible repositories the battery is located, designated for ideal remanufacturing, for low-capacity remanufacturing, or recycling, as distinguished in Figure 5. With this minimal resource-intensive process, an EOL-RCB is dismantled, and the condition of the extracted battery module is assessed to integrate representative properties into the decision-making process for the subsequent recirculation category.

5.2 Analysis of Mitigated Risks

In terms of the identified SPTF (see Table 6), No. 1, No. 2, No. 4, No. 7 and No. 8 were addressed and the top event of personnel injury evaded with the selected concept 4 due to the physical separation of the hazardous product from the operator through the glovebox and rubber gloves. No. 6 could not be addressed as outlined in Chapter 4.2.1. Furthermore, the lack of training can be addressed by providing intuitive process operation steps, usage manuals, and illustrations of good and bad operation outcomes. In addition, PPE such as rubber gloves in the glovebox provides safety in the event of failures, including failure due to a lack of training. Similarly for the process after the glovebox, in which at least rubber gloves should be utilized to avoid direct contact with battery terminals. The dangerous hasty working approach was addressed by dividing the disassembly process into three workstations and one SOH classification station. This measure leads to a minimal amount of two or three tasks per workstation and therefore relieves pressure on the operator.

At this stage of development evaluation all other identified risks in the PHL and the derived Fault Tree are shortly evaluated as well. Within the electrical error section, PHL-3, the exposure to higher temperatures, is addressed by keeping a moderate temperature, such as a standard ambient temperature of 25 °C and pressure of 1 atm, at the workstations and particularly within the glovebox. Physical damage to battery cells, PHL-4, and electrolyte leakage, PHL-2, can only be observed after the external covers are removed, which is why this action is conducted within the glovebox to not expose the operator to harmful substances or gases. The risk for thermal runaway, a major problem for EVBs, is decreased, although the consequences for RCB modules of five to six cells are limited in comparison to EVB packs of 70 to hundreds of cells [72]. In terms of the BMS, puncturing energized components, PHL-7, it is only possible at workstation 3, in which the battery pack is exposed to a sharp wire cutter. Here, at workstation 3, the physical separation is a key factor. This insulation also prevents negative consequences to humans due to indirect contact or contact with non-insulated live wires. To mitigate errors in the disassembly sequence or the use of inappropriate tools as well as a misidentification of parts, four workstations were defined to minimize tasks and tools at each station that can be confused (PHL-12, PHL-13, PHL-14, PHL-18). In terms of PHL-22, consequences are limited to the enclosed space within the glovebox. PHL-23 is addressed by providing proper tools such as a drill bit extension to remove the green frame of the Ryobi battery pack. PHL-24 is mitigated by minimizing the distances between the workstations, such as allocating all of them on countertops directly next to each other with limited space in between. PHL-25 and PHL-26 are mitigated by extracting internal components in the glovebox. To ensure that no harmful gases are inhaled at workstation 2 as well as to identify all damages to the battery cell only in the glovebox, the removal of the external covers must be performed in the glovebox. In conclusion, this process represents a realistic concept to mitigate numerous hazards during a manual, RCB disassembly to facilitate operator safety while enhancing the sustainable recirculation of RCBs.

5.3 Evaluation of Concept Robustness

Also, the process robustness and flexibility must be investigated, in how far the process handles other types of RCBs. Closer examination of the flowchart and the workstations yield that processing of other battery types is possible until different screws are identified which require other bits than the ones provided, if not an entire bit-set is acquired. Yet, four out of five RCB models use the same screws which leads to the hypothesis that many hand tool drill battery models are manufactured with this external screw type and must be further investigated. On the interior, however, only one of four batteries, Ryobi, contained other screw models. Thus, no refence is given whether different screws are typically utilized on the inside and whether this represents an obstacle. At workstation 3, it is possible that the glovebox is insufficiently spacious to handle different, larger, types of batteries. Additionally, the waste containers or repositories may be insufficient in size, necessitating more frequent emptying. Lastly, the SOH assessment must be adapted to other battery types which may require larger amounts of current or possess dimensions that may be incompatible with the selected measurement technique for the examined RCB types. This is of particular interest as DEWALT, as one out of five types exhibits a different battery module. Therefore, it requires a setup that differs from the 18650-type battery module measurement setup. The process steps are designed to accommodate the detected number of screws, cables, metal connectors, and other components within the RCB pack to facilitate process flexibility, adaptability, and robustness.

5.4 Assessment of Concept Feasibility

To assess the feasibility an equipment cost estimation must be conducted. However, the SOH equipment is excluded from the listings, as the assessment method is yet to be fully developed and validated in separate studies. Table 9 presents a list of the objects, identified by workstation WS, along with the necessary quantity Q and the respective retailer. Sources of the items are provided in Appendix F. Items utilized in multiple workstations are assigned WS 0.

Table 9: Cost estimation of the manual RCB disassembly concept

WS	Item	Q	Cost per item	Retailer
1	Multimeter	1	20 USD	Harbor Freight
1	Spare battery (LR44)	2	0.3 USD	Amazon
0	Repository	9	1.4 USD	Global Industrial
2	Hand tool drill	1	20 USD	Habor Freight
2	Bit Set	1	10 USD	Habor Freight
2	Drill bit extension	1	9 USD	Habor Freight
3	Wire cutter	1	2.8 USD	Habor Freight
3	Sand, 2 kg	1	0	-
3	Rubber sheet	1	18	Rubber Sheet Warehouse
3	Grounding Cable	1	14.1 USD	MRO Essentials
3	Glovebox	1	~ 100 USD	(see Appendix E)
4	Rubber gloves, pair	1	1.9 USD	Global Industrial

This list results in an estimate of approximately 110 USD initial disassembly tool costs, excluding the glovebox. A purchased glovebox is estimated to cost approximately 100 USD, as detailed in Appendix E. Combining both results in the total initial disassembly line equipment costs of 210 USD.

With resale values obtained by Peters, 0.59 USD material recycling value per 18650-type cell [73], and Sodhi, additional 2 – 3 USD resale value per remanufactuarable pack of five cells [74], new cells cost roughly 4 USD per cell [75], a cost estimation is conducted. By balancing the disassembly process to process one RCB every minute, and a downtime of approximately 30 minutes per day, a total of 450 RCBs is disassembled during a 8-h workday. The process line balancing requires eight human operators and conservative assumptions of 85 % are classified into the recycling category (material value 0.59 USD/cell [73]), 10 % categorized into lower-quality remanufacturing (additional value 2 USD/module [74]) and 5 % into high-quality remanufacturing (additional value 3 USD/module [74]) is applied. Utilizing these battery resale values yields a revenue of 585 USD per day. This value does not include facility or subsidairy costs. An elaboration on this economic estimation can be found in Appendix G. Moreover, this concept demands less equipment compared to other concepts under investigation, resulting in reduced labor and setup time from an economic standpoint. Thus, this approach effectively meets the minimal resource objective while prioritizing enhanced safety measures. In conclusion, the equipment is selected to meet the objective of being procured virtually everywhere while minimizing costs and still satisfying safety requirements, yielding an expectation of high realizability.

To assess the process quality quantitatively, the following metrics are considered to evaluate process feasibility:

1. **Yield (Y):** The yield of a process represents the percentage of successfully processed goods. It can be calculated using the estimated production number (P), the percentage of ideal parts (I), and the percentage of

parts reworked for sale (R). For this disassembly line, I represents high-quality remanufacturable modules, R represents lower-quality remanufacturable modules, not reworked scrap, and P represents the number of processed RCBs. The formula for yield is: $Y = P \times I + P \times R$

Given: $P = 450$ RCBs, $I = 5\ \%$, $R = 10\ \%$

The yield can be calculated as:

$$Y = 450\ \text{RCBs} \times 0.05 + 450\ \text{RCBs} \times 0.10 = 22.5\ \text{RCBs} + 45\ \text{RCBs} \approx 67\ \text{RCBs}$$

2. **Throughput (H):** Throughput quantifies the number of products processed (P) divided by the respective production time (T, in h). The equation for throughput is: $H = \frac{P}{T}$

   Given: $P = 450$ RCBs, $T = 8$ h

   The throughput can be calculated as: $H = 450\ \text{RCBs} / 8\ \text{h} \approx 56\ \frac{\text{RCBs}}{\text{h}}$

Das and Naik confirm the use of valuable output qualities of the process, such as yield and throughput, to assess disassembly process quality [76]. In conclusion, a yield of $Y = 67$ RCBs which are categorized into the two upper target categories, and the throughput of $H = 56\ \frac{\text{RCBs}}{\text{h}}$, roughly one RCB per minute, represent a satisfactory quality of the manual RCB disassembly line.

For a comprehensive assessment of the process quality, feasibility and added value, the following section lastly presents environmental impact estimations resulting from the implementation of the developed disassembly process.

The majority of the processed batteries comprise 18650-type LIB cells. Therefore, this type is the focus for estimating the environmental impact. Salgado Delgado et al. report, that the global warming potential (GWP) of these battery cells is equivalent to 1.4 kg CO_2 (CO_2-eq) per cell, a figure that encompasses the material impact, manufacturing, and usage phase [77]. Conversely, Botejara-Antúnez et al., report a higher GWP contribution of 2.1 kg CO_2-eq per battery cell [78]. This discrepancy in reported values, as discussed by Ciez and Whitacre and Chen et al., underscores the ongoing research and need for standardization in GWP assessment methodologies [79,80].

Regarding the recycling process of a 18650-type LIB cell, Salgado Delgado et al. estimate that recycling contributes 0.0114 kg CO_2-eq to global warming [77]. Additionally, Salgado Delgado et al. evaluate other impact categories such as the human toxicity potential of the recycling process, estimating it to be 0.144 kg 1,4-dichlorobenzene equivalents per 18650-type LIB [77]. Chen et al. report different GWP contributions ranging from 0.036 kg CO_2-eq to 0.353 kg CO_2-eq per cell, depending on the recycling method and LIB cathode material [80]. For the conversion of values per functional unit kWh, the capacity of one extracted 18650-type LIB of 7.2 $\frac{\text{Wh}}{\text{cell}}$ is multiplied by the GWP contribution value (in $\frac{\text{kg CO}_2\text{−eq}}{\text{kWh}}$), with 1 kWh divided by 1000 to obtain Wh.

Tasala Gradin et al. report that manual disassembly of a product results in 9 % less GWP contribution compared to shredding, emphasizing the environmental benefits of disassembly procedures [81]. Additionally, Chen et al. find that remanufacturing LIBs using material from EOL batteries, reduces the GWP of manufacturing processes by 20 – 32 %, depending on the LIB type [80].

Detailed GWP contribution values regarding different impact categories can be obtained from the works by Botejara-Antúnez et al. [78], Chen et al. [80], and Salgado Delgado et al. [77]. In conclusion, at least 9 % of the GWP of landfilled or shredded RCBs can be saved by implementing this process, with the potential to save up to 32 % by remanufacturing [80,81]. In summary, the process feasibility and quality are assessed by several key metrics:

- **Cost estimation:** 210 USD equipment costs
- **Revenue:** 585 USD per day, providing margin to cover facility and subsidiary costs
- **Yield**: 67 upper quality remanufacturable RCBs per day
- **Throughput**: nearly 1 RCB per minute
- **Environmental impact**: potential reduction of up to 32 % GWP otherwise contributed by landfilling and shredding EOL-RCBs

All of these aspects contribute to the overall process quality and feasibility, advocating for its implementation.

5.5 Exploration of Automation Potentials

This manual, safe RCB disassembly concept shows process enhancement opportunities through automation measurements which are explored in the following, employing a forward approach along the developed process line. In general, automation concept 3 displays numerous automated design solutions that can be implemented. Nonetheless, the following section describes automation measures which are considered as sensible next progression levels. Firstly, an upstream battery identification can be performed by a **sorting mechanism** by utilizing a camera and machine learning algorithms. This application can discard models like Makita1 which cannot be manually disassembled, or it can serve to identify damage as part of the optical inspection. This implementation could sort out 20 % of all investigated RCB types and hence yield a considerable work reduction for workstation 1. Next, fueling the result of the **multimeter pre-test into an algorithm** and create a machine-generated unambiguous decision shows potential to mitigate human error during the value obtainment and interpretation. Within the glovebox a utilization of **thermal imaging camera** enables the identification of areas with critically increased temperatures which can lead to sparks, thermal runaways or others, prior to the actual occurrence. This determines when to stop an operation to allow the area to cool down or to be discarded. Moreover, the **sand storage and supply** are subject to automation, as reaching, gripping and targeting the sand on the affected area can cost more time than available to react to the hazard. A **chute** from one of the top corners of the boxes could direct the sand to the center of the glovebox, the major place of operation. One way to implement it is by employing a foot pedal for signaling and controlling the dosing of sand. Additionally, the separated parts from the targeted battery module must be removed from the glovebox in order not to clutter the limited workspace. This can not only be incorporated by corresponding channels but by being manually pushed or automatically gliding onto a **conveyor belt** by a gravity-fed, slanted glovebox bottom. The transported parts can then be sorted into larger respective repositories, avoiding the need to frequently empty the containers within the glovebox. Not only the discarded parts but also the batteries can be transferred to the next workstation by **conveyor belts** which mitigates the need for operators to leave their workstation. Lastly, the SOH assessment shows automation potential with the objective of mitigating human interpretation errors. By limiting human responsibility to solely insert the batteries into **cavities** and receive **unambiguous signals** that determine the repository that the battery is assigned to. A red, yellow, or green light can be employed for the three different target categories recycling, low-capacity remanufacturing, and ideal remanufacturing respectively. This visual signal depends on the automated measurements and subsequent calculations, which are conducted by tailored DAQ systems, initiated by the successful insertion into the battery cavity mold, to yield a SOH value.

These automation potentials target the deficiencies of human operators, such as interpretation errors as well as low processing and reaction speed. These properties can be complemented by the strengths of machines, which can be programmed to act according to a predefined decision tree and operate with a preset speed that is not decelerated by sentiments, shock, or surprise.

5.6 Discussion of Limitations

For a critical evaluation, the limitations of the developed concept as well as the performed research are discussed to validate the approach.

5.6.1 Limitations of the Developed Concept

With respect to the pre-test of the battery conducted with the multimeter, a few shortcomings have been identified. Firstly, it is not possible to determine the operability of the battery with complete accuracy based on the voltage alone. To obtain a reliable, representative value, it is necessary to perform additional measurements and calculations. Secondly, the multimeter is subject to the operator's performance. If the operator is unable to establish proper contact between the correct battery terminals and the probes or engages in any other form of erroneous conduct, the result will be inaccurate and may result in the loss of potentially usable batteries. This shortcoming can be addressed by providing best-practice visualizations that illustrate the ideal positioning of the probes on the battery terminals. These illustrations can also depict critical external battery damages and thus, propose actions that do not necessitate the use of hands or disturb the measurement, such as checking for these critical damages, while allowing the multimeter to settle on a value. Furthermore, the result of the multimeter as well as of the SOH measurements and calculations are subject to the device and method accuracy. Since the precision of the result is limited by the internal measurement error and accuracy, error propagation must be considered, as the calculations are also limited by the level of abstraction of the model used. However, the multimeter is exclusively employed for the initial filtering of defect samples and does not require high precision or accuracy. In the context of EOL-RCB disassembly, it is important to remove defective samples, as they may represent the majority, and can result in unnecessary work, if not excluded. Moreover, the optical inspection is susceptible to attentiveness and human error and undetected external damage or leakage potential. Such issues can result in increased risks and SPTF can be triggered, limiting successful risk aversion through incorrect operator behavior.

In terms of process time, estimations are made in Appendix G, but particularly in the initial operation phase, the cycle time is a considerable limitation. An optimistic assumption of four required attempts to successfully conduct the pre-test for one qualifying RCB, an estimation of one minute for each pre-test and screw removal, and two minutes for workstation 3, as the doors must be opened and closed to insert the RCB and sufficient time for inspections and careful operation is included, and an estimate of five minutes for the SOH assessment and categorization, leads to a tentative disassembly time of twelve minutes. This process duration is constrained by the required material transfer time between stations. This time can only be shortened to a finite extent.

5.6.2 Limitations of the Employed Methodology and the Research

Makita1, the second RCB of the conducted disassembly experiments, yielded the first significant proof of a limitation of this research: several products, such as RCBs, are **not designed for disassembly**. This represents a limitation of the study, which has also been identified by Schäfer et al., and underscores the need for further advancement in this research field [29]. Thus, the first conclusion is to avoid destructively detachable connections in RCB manufacturing to allow safe recirculation. Another aspect to be discussed is that the disassembly experiments were not conducted with the **same tools** as in the current use case as outlined in Chapter 2.3. Nevertheless, the electric screwdriver represents a more efficient and ergonomic screw removal tool, while the wire cutter, in contrast to a chisel and hammer, achieves greater efficiency for cutting operations, thereby fulfilling two objectives of the anticipated disassembly process and likely to be selected as an inexpensive design solution. Furthermore, the investigated batteries include more dangerous substances than more stable battery types such as $LiFePO_4$-batteries which could be installed to reduce risks and improve the ease of disassembly and recirculation [82]. Similarly, solid-state LIBs or sodium-based batteries are safer approaches that target risks by **addressing the source itself,** significantly reducing the occurrence of electrical hazards [83,84].

Additionally, RCBs within the scope of this research are composed of battery cells, such as 18650 cells, with an electrical charge of 2.0 Ah, a voltage of 3.6 V, and a capacity of 7.2 Wh. This raises the question of why extensive safety measures are necessary, given these values are lower than other battery cells, such as the INR21700-50E model, which can reach up to 4.8 Ah and over 17 Wh [73]. One might assume that lower values result in reduced risks like shocks, short circuits, and explosions, which might not cause significant harm to operators. However, this issue must still be addressed, and additional safety measures implemented because the **health condition of the operator** cannot be foreknown. Undiagnosed health conditions, such as heart issues, pacemakers, or neurological disorders, can increase operator sensitivity and risk. To ensure the safety of all operators, additional risk-mitigating measures, such as the designed RCB disassembly station, are highly recommended.

Next, the EOL-RCB collection for disposal or recirculation represents another limitation, which must be mentioned. In order to achieve high recirculation and remanufacturing rates, more EOL-RCBs must be collected, as, according to Gu et al., in China, the largest LIB production and consumption nation, almost every second person stores EOL-RCBs at home and more than 90 % of the interviewed people did not know where to dispose, let alone recirculate LIBs [10]. The European Union stated that information on spent battery handling must be publicly available and included in a battery passport, which resembles an abstract concept to improve this lack of information [67]. Hence, to effectively increase the recycling and remanufacturing rate of 5 %, **education about proper RCB recirculation**, and legislative measures to subsidize the recirculation of spent RCBs by implementing safe disassembly processes, must be carried out to eliminate these constraints of this research field [9].

5.7 Answering Research Questions

To develop a RCB disassembly line, an elaborate risk identification was performed. After examining different systematic risk identification methods, the justified selection was made to combine a Preliminary Hazard List and a Fault Tree Analysis. 26 preliminary hazards (see Table 5) and eight Shortest Paths To Failure (see Table 6) in the fields of electrical, physical product, environment, and human errors were derived as relevant risks to human operators within a manual RCB disassembly process. This collection serves as an answer to research question RQ1.

Based on the examined risks, a list of potential prevention measures, hazard reaction techniques, and additional auxiliary prevention measures was compiled, and the majority is recorded in the morphological box (see Figure 7). The development of workstations incorporated additional considerations to mitigate identified risks, in excess of the SPTF, such as by limiting the number of tasks and tools within a workstation to avoid the usage of inappropriate tools (PHL-14), or operator error in the disassembly sequence (PHL-12) (see Chapter 4.5.1). However, SPTF root causes such as a lack of training could only be addressed to a limited extent, as the choice of operators has a large impact on the effectively exposed risks and the level of expertise or ignorance, which cannot always be addressed by error-proof process design. Similarly, for hasty working methods, the reduction of tasks within a workstation can lead to less urgency but not all influences and sources for the complexity of human behavior could and can be limited by the disassembly process design.

Regarding RQ3, the upper levels of Potting et al.'s R-strategies - refuse, rethink, and reduce - are not applicable in the process of sustainable recirculation of RCBs, as the batteries are already in existence. By the justification of safe further utilization, as detailed in Chapter 4.2.2, the batteries are assigned to the classifications of the R-strategies remanufacturing – employed in two stages: a higher quality remanufacturing and a low-capacity remanufacturing – and recycling, to facilitate recirculation.

Finally, the implementation of a SOH assessment of the batteries justifies the degradation-based classification of EOL-RCBs into the target categories. The closer a condition is to its initial state of sale, the higher the quality of recirculation of the extracted battery. Therefore, the three sections upper bound (higher quality remanufacture: 100 – 80 % recommended), middle ground (low capacity remanufacture: 80 – 70 % recommended), and lower bound (recycling: 70 – 0 % recommended) were identified into which the batteries can be categorized into according to the obtained SOH information.

CHAPTER 6: CONCLUSION

To conclude, the conducted master's thesis is briefly summarized, and the resulting implications of this study on further research are outlined.

6.1 Summary of this Study

To conduct this research, experiments involving manual disassembly, were conducted and the standard described in VDI 2221 supported the conceptualization of the manual RCB disassembly process. By the determination of functions, the creation of a process flowchart, the comprehensive risk identification, and the collection of solution principles which is visualized in a morphological box, a methodical, systematic approach was employed. This study has focused on the implementation of three key objectives; sustainability, efficiency, and safety, within the concept development. Sustainability has been addressed by the extension of product life by successfully assigning EOL-RCBs to target categories to facilitate recirculation. Efficiency has been considered by enabling the disassembly of various RCB types without the need for significant financial or labor resources or process adaptations. Lastly, safety measures have been implemented which reduce the identified risks and mitigate SPTFs. This study fills the market and research gap for a robust, safe, manual RCB disassembly process, comprising four workstations and including a comprehensible process description.

6.2 Implications for Future Work and Industry

The results of this study provide insights into the implementation of SOH considerations and highlight the need for further investigations on appropriate EOL-RCBs SOH assessment methods. The objective for that is twofold: firstly, to fulfill the need for comprehensive and **representative SOH properties** to categorize them for recirculation strategies, and secondly, to enable **real-time application** in terms of quick or large batch measurements, thus facilitating the implementation of the findings in industrial or facility settings. This SOH research is of particular interest as it raises the profitability and viability of the EOL-RCB disassembly process while providing accurate measurements. The considered **two-stage SOH assessment** is subject to exact measurement techniques and further research as well. Similarly, the question of whether to employ **single-cell or module SOH testing** poses another research question, not addressed by this thesis, which warrants further exploration for the implementation of this concept. Two key factors, measurement accuracy and efforts of rejoining cells, should be considered in this context. Integrating the perspectives provided by Kampker et al. offers valuable insights and can guide subsequent studies in addressing this question comprehensively [28].

Regarding the developed process, it is recommended that a further inspection be conducted with a view to alternative low resource-intensive **safety measures** as well as on the detailed **design of the glovebox** to enhance the RCB disassembly process. While this master's thesis focused on the disassembly of hand tool drill batteries, it calls for a complementary study that analyzes the **applicability of the results**, like the derived flowchart and disassembly workstations, on other types of EOL-RCBs.

This work illustrates the limitations of non-detachable connections in the effective disassembly and recirculation of products. Thus, irreversible manufacturing steps for non-biodegradable material must be avoided to enable a circular economy. This underscores the need for further research on **detachable connections**, which ensure safe operation time, but can be dismantled by trained personnel while remaining simple and inexpensive to manufacture.

Moreover, to increase the rate of recirculated RCBs, it is imperative to address the most significant deficit, namely the lack of information. An expansion in the number of spent batteries being redirected to disassembly processes and facilities holds the greatest potential. Consequently, it is essential that **education and awareness** about the proper disposal and recirculation of products, such as RCBs, be effectively disseminated and raised to enhance the recycling and recirculation rate, as opposed to landfilling. This calls for further investigations of effective ways of informative calls to action on products, particularly in developing countries. However, it is not limited to these as more sustainability and a circular economy are objectives that are being pursued by nations across the globe. It is a goal that transcends national boundaries and represents a unifying element between all countries, calling for further research in and for every nation.

APPENDICES

Appendix A – Selected Technical Specifications of Examined Battery Models

Table 10: Selected technical specifications of the examined battery modules

Brand	Series Name	Model Number	Type	Voltage (V)	Capacity (Ah)	Tower structure	Source
DEWALT	XRP	DC9096	Ni-Cd	18	2.4	Yes	https://www.dewalt.com/product/dc9096/18v-xrp-battery-pack
DEWALT	XRP	DC9097	Ni-Cd	18	2.4	Yes	
DEWALT	XRP	DC9098	Ni-Cd	18	2.4	Yes	
WORX	MAX	WA3525	Li-Ion	20	2.0	No	https://www.worx.com/20v-maxlithium-battery-2-pack-wa3525-2.html
WORX	MAX	WA3526	Li-Ion	20	2.0	No	
Makita		BL1815	Li-Ion	18	1.33	No	https://www.makitatools.com/products/details/BL1815
Makita		BL1815	Li-Ion	18	1.33	No	
Makita		1234	Ni-MH	12	2.6	Yes	https://www.makitatools.com/products/details/193157-5
Makita		1234	Ni-MH	12	2.6	Yes	
Makita		1234	Ni-MH	12	2.6	Yes	
Makita		1234	Ni-MH	12	2.6	Yes	
Ryobi	ONE+	P190	Li-Ion	18	2.0	Yes	https://www.ryobitools.com/products/details/33287173358
Ryobi	ONE+	P190	Li-Ion	18	2.0	Yes	

Appendix B – Fault Tree

The following Figure 9 illustrates the different types of events and respective shapes. The choice of undeveloped events as root causes is made to indicate the relevance to this master's thesis. Further investigations on events illustrated as undeveloped do not provide additional value to the progress of this research. Within the physical product error branch, the damaged battery cell is listed one time as an intermediate event with subsequent causes and right adjacent to it as an undeveloped event. This is done to avoid repetitions of the same branch which is developed in direct proximity. Similarly, in the environment branch, the damaged battery cell is regarded as an undeveloped event to avoid duplications because it is developed in the physical product error branch. This is applied to the events of Misidentification of Parts and Damaged Battery Cell. Furthermore, the cause level (first-level cause to fifth-level cause) is indicated by assigning lighter colors the farther the cause can be traced back. A second-level cause is darker than a third-level cause. According to these colors, the identification of SPTFs is simplified by searching for the same color root causes, which have the same depth. Since the top-level event and the first-level causes are illustrated in Figure 4, Figures 10-13 visualize the respective branches.

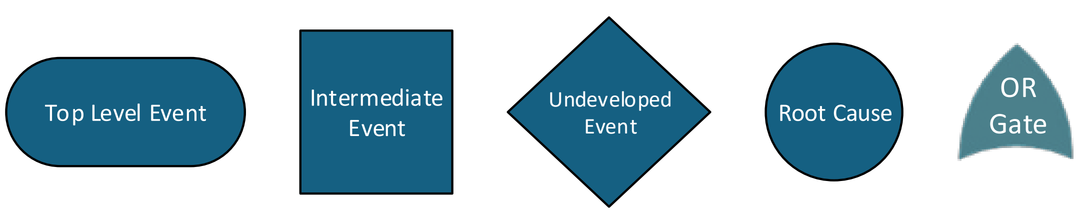

Figure 9: Legend for different shapes within the Fault Tree

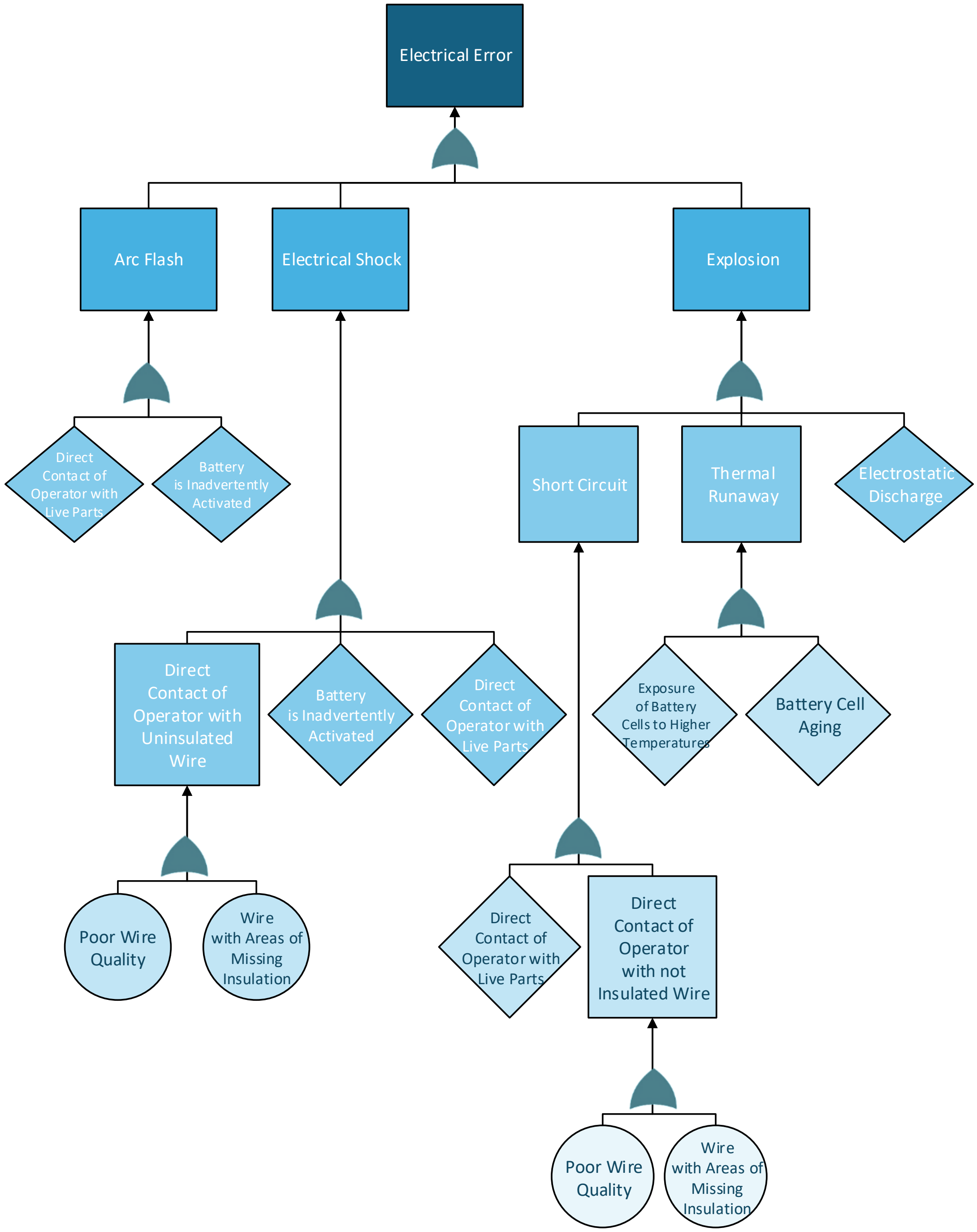

Figure 10: Fault Tree Branch “Electrical Error”

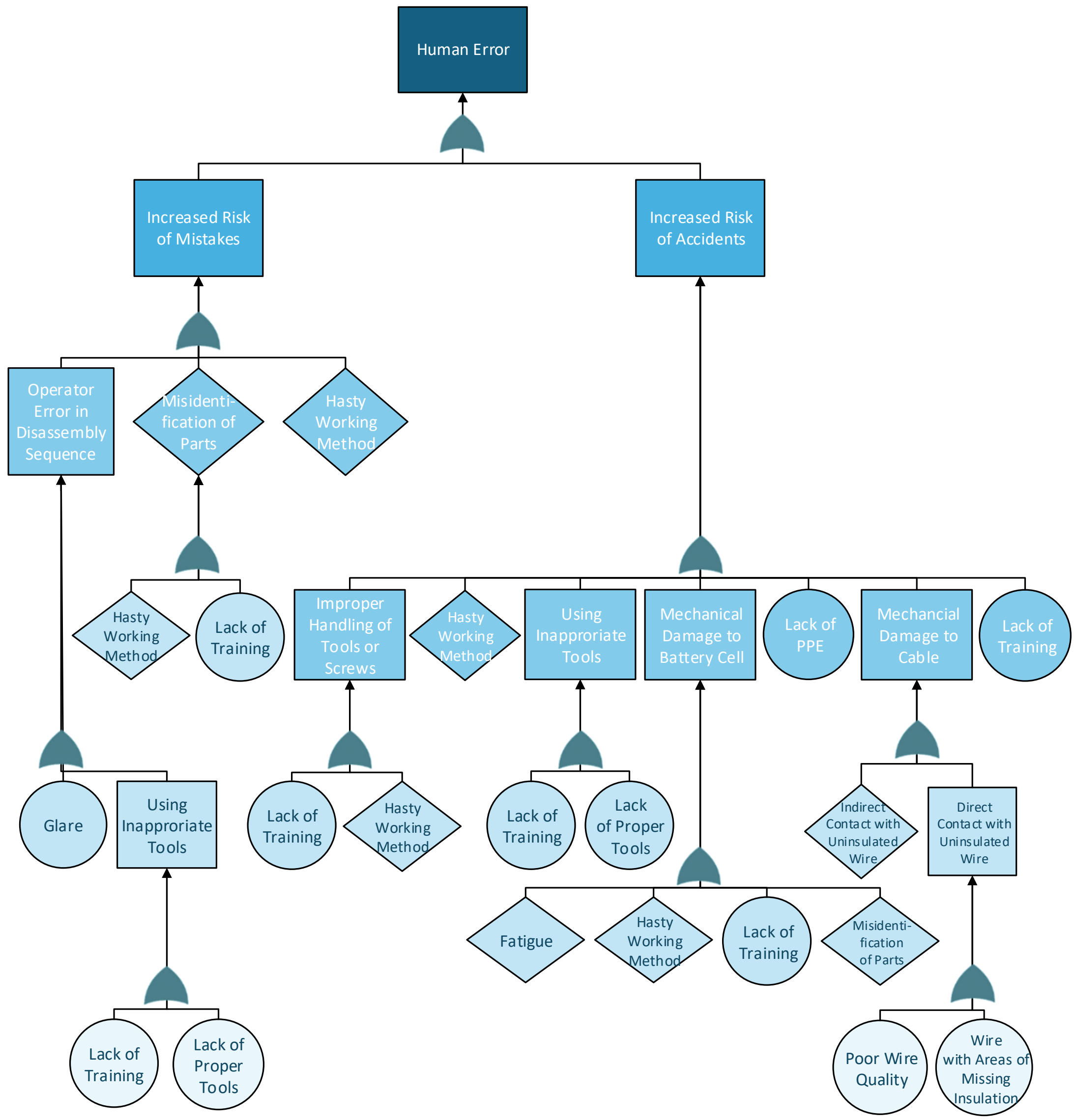

Figure 11: Fault Tree Branch “Human Error”

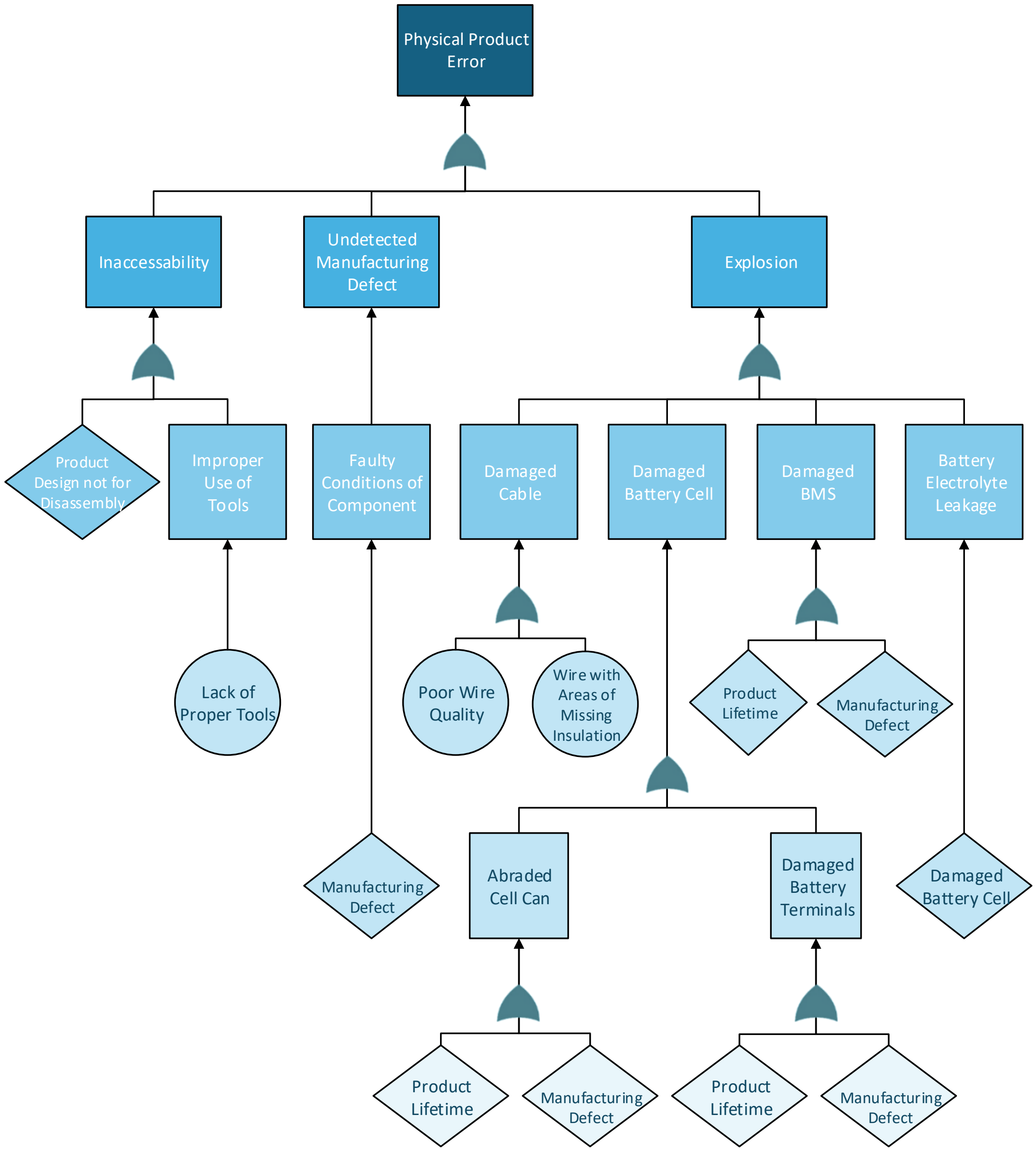

Figure 12: Fault Tree Branch “Physical Product Error”

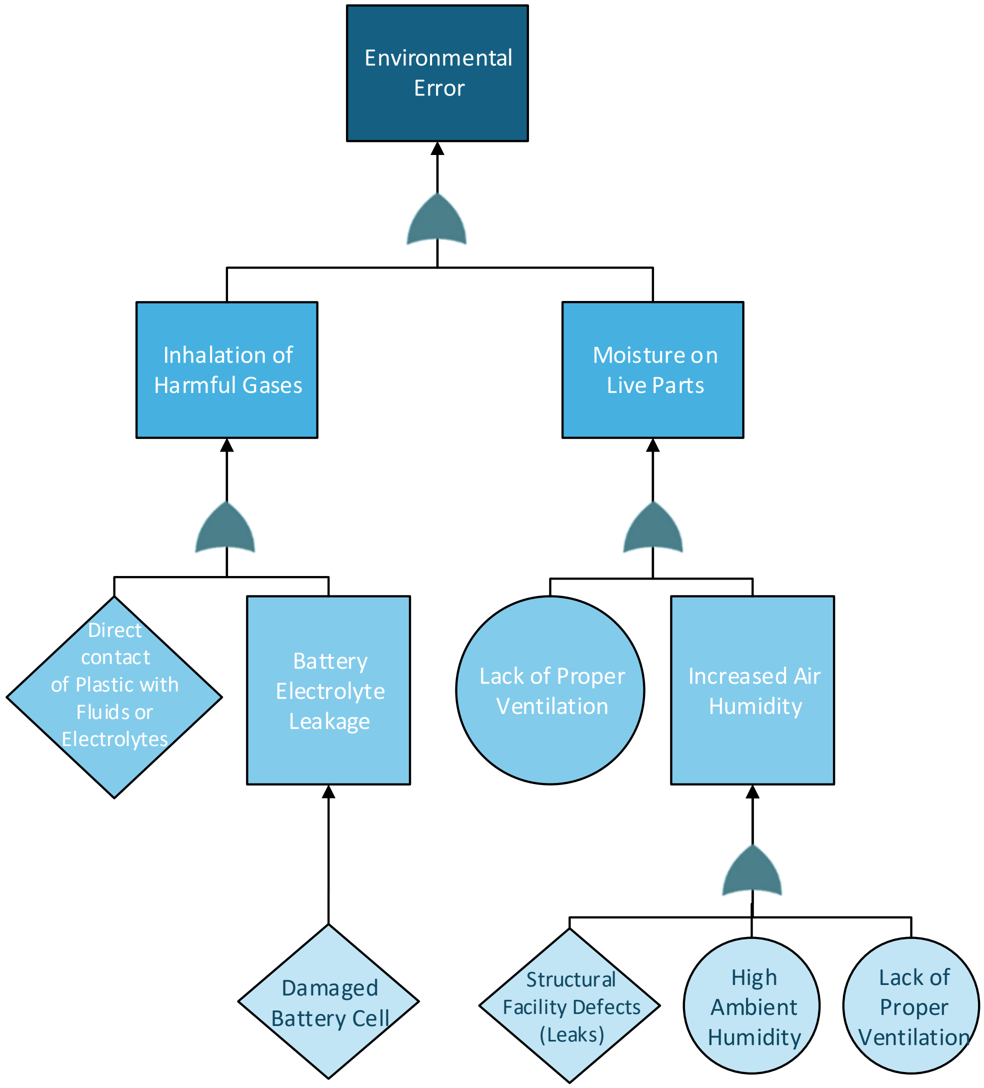

Figure 13: Fault Tree Branch “Environmental Error”

Appendix C - SOH Assessment Methods

To assess the SOH and other battery properties, quantities like the current, voltage, impedance, or temperature of batteries are measured [65]. Employing these measurements to conclude the status of internal degradation of the chemical substances [70]. Using these and elaborate measurements to derive the SOH is called direct SOH measurement, whereas an indirect measurement employs calculations based on simple acquired values. The more elaborate the acquired values and measurements are, the more precise and accurate the calculated results and conclusions on the SOH. For the target environment, with limited available tools and limited or non-existent information on battery usage or battery pack aging history, methods that require such data cannot be considered. In the following SOH assessment methods are introduced which do not rely on data of the previous battery operation time, also called "historical data" of a battery, but rather include information from datasheets of the initial battery model state of sale. Consequently, methods such as Internal Resistance Analysis, or Acoustic Analysis are not considered, also regarding the extensive laboratory equipment. However, to provide one option for potential other frameworks, stakeholders, or different environments, the state-of-the-art method of Electrochemical Impedance Spectroscopy is shortly outlined.

Coulomb Counting

According to the findings of Berecibar et al. or Pradhan and Chakraborty, Coulomb Counting is the most used method to assess the SOH of RCBs [21,22].

Even though it is mostly employed to calculate the state of charge of batteries, the SOH can be determined as well. This direct measurement approach counts the transferred amount of charge during a full charge and discharge cycle and employs the formula given in Chapter 2.1. The relation between the maximum releasable capacity and the originally stated amount of capacity is the strategy to obtain a SOH value [85]. Therefore, it does not incorporate more internal properties and represents a rough estimation. Furthermore, Coulomb Counting does not require extensive equipment and is therefore less expensive and less time-consuming. Nonetheless, Ng et al. recommend re-assessing the SOH in the event the battery condition assumes one of the two extreme conditions of discharged or fully charged [85].

Capacity Measurement

Similarly to the Coulomb Counting, the shortest path to achieve a ratio of the current battery capacity divided by the nominal capacity is a direct capacity measurement. Therefore, to assess the SOH a discharge device can be employed that provides the function to measure the current capacity. The current capacity can then be divided by the originally rated capacity of the battery. However, this approach can only be utilized for a rough estimate and cannot be used to achieve high accuracy or reliability, since it does not take any other properties into account. Despite the disadvantage of reduced accuracy, this method is notable for its speed and low costs.

Two Pulse Load Test

As an indirect measurement, the Two Pulse Load Test (TPLT) provides a method to test the battery condition without historical data on the battery. However, a series of experiments with the investigated battery models needs to be conducted to obtain auxiliary properties, such as the voltage difference ΔV over the state of charge, and two constants (c_1 and c_2) which are used for the SOH calculations, as explained by Coleman et al. [70]. After receiving the necessary values, the battery cell under investigation is exposed to three different experiment phases which are visualized in Figure 14. Within the first phase, Coleman et al. describe that the battery is in an open circuit. After a stabilizing time, the second phase is entered. In this section, a current phase, in which a known value of a pulse load is applied to the battery for a short period, followed by a recovery phase, in which the current is removed. The voltage recovers to a local maximum value again, as illustrated in Figure 14, and is measured over the entire period. For the subsequent third and last phase, the process of applying the same pulse load of current over the same amount of time is repeated and followed by another recovery phase. The voltage difference that results from the newly reached minimum voltage at the moment the current is removed, compared to the local maximum voltage at the end of section two is the relevant difference ΔV which can be related to the SOH of the battery according to the following relationship:

$$\boldsymbol{SOH = (C * (c_1 * \Delta V + c_2))^{-1}}$$

Here C denotes the initial nominal capacity of the battery cell, which can be obtained from technical data sheets. As a consequence, TPLT represents a method that in operation takes a minimal amount of time but requires extensive experiments prior to the actual measurements and calculations [70]. Also, Coleman et al. announce that an accurate, sensible application of TPLT is only conducted in the area that shows a linear proportionality between ΔV and the state of charge of the battery [70]. For EOL-RCBs, this region begins at more than 60 % state of charge, which means the three-phased experiment should be performed with batteries of at least 60 % charge [70].

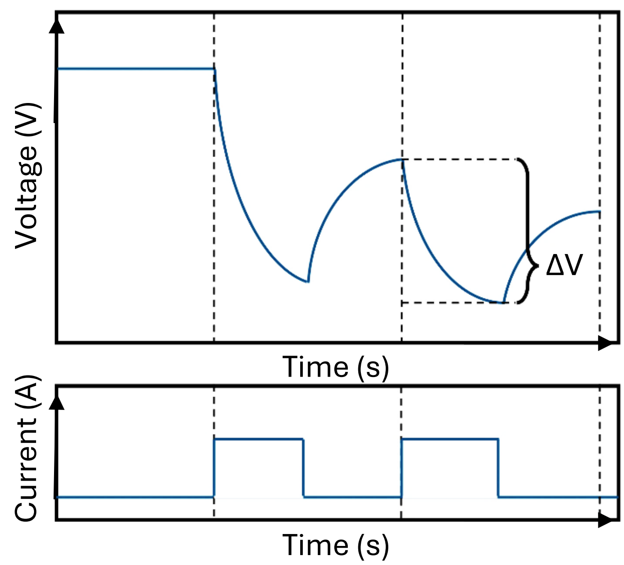

Figure 14: Two Pulse Load Test three-phased measurement (adapted from Coleman et al. [70])

Electrochemical Impedance Spectroscopy

Lastly, Electrochemical Impedance Spectroscopy (EIS) is a direct measurement method which considers not only the capacity ratio but incorporates the internal impedance into a more holistic SOH approach. Since the impedance shows a direct correlation to battery aging, EIS leverages the relation between voltage excitation in the form of a sinus signal over a multitude of frequencies and the resulting current response to calculate the impedance [86]. The measurements can be analyzed concerning amplitude, frequency, and phase relationship and are typically illustrated in Nyquist or Bode plots, which allows for a visualization of the calculated impedance values [86]. This data can then be fitted to a model, assessing the SOH based on internal key properties or employing a data-based approach that incorporates data from other batteries or historical data [86]. EIS is known for its limited invasiveness on the battery as well as the close to steady-state conditions. Furthermore, EIS is not limited to a certain range of battery performance, and therefore, shows broad applicability next to a high precision and accuracy, provided it is well calibrated. On the other hand, the EIS method requires elaborate electrochemical equipment and measurements over a selected frequency range with extensive calculations and model fitting, prolonging the SOH assessment duration.

Other methods are not considered, as the goal of this SOH assessment is to determine the condition of the EOL-RCB and provide useful information for further battery utilization. To provide confidence in the results and ensure accurate SOH values, it is necessary to obtain data, such as maximum discharge current, from the state-of-sale datasheets of the examined batteries.

Appendix D – Detailed Evaluation of Possible Concepts

The criteria for evaluation are cost, time, and quality. Each criterion is assessed for each concept. The SOH method is excluded from the evaluation, as the focus is on the added value from this step rather than the distinct method itself. Consequently, the SOH method can be easily substituted and re-evaluated. With the assigned weights and values, the scores range from a minimum of -30 to a maximum of 30.

Concept 1

This concept, aimed at minimizing resource usage, requires an initial investment in a multimeter, manual screwdrivers of various shapes and sizes, sand, a utility knife, and materials to construct and ground a glovebox. These limited and relatively inexpensive tools result in a satisfactorily low initial investment cost (+). In terms of resource costs, the necessary resources include human labor, multimeter batteries, and glovebox grounding equipment. This minimal requirement leads to a positive evaluation of this criterion. Finally, the operational costs are confined to human labor, as none of the selected design solutions require a power supply. Consequently, this aspect also receives a positive evaluation. This concept does not require extensive further development except for potential adaptations of the assemblable glovebox which results in a satisfactory **fulfillment** of short development time (+). No parts within this concept require a calibration which results in an excellent **fulfillment** of short calibration time (++). Due to the completely manual performance such as the usage of manual screwdrivers and the laborious, strenuous utilization of a utility knife for cutting operations, the concept yields a highly unsatisfactory assessment of the operation time (- -). The screwdriver and the glovebox intuitively align with the necessary process steps. However, the use of a utility knife, the absence of specifically designed fixtures, and the numerous human error potentials, particularly during pre-testing, hinder process simplicity. As a result, the evaluation for high process simplicity is neutral (o). Conversely, the absence of special fixtures increases the potential to integrate other battery models or adapt the procedure easily, earning a positive evaluation (+) for process flexibility. Most importantly, this concept significantly mitigates SPTF risk (+). Despite the high reliance on manual labor, the glovebox provides shielding and protection for the operator during the most hazardous steps. **Result: 11**

Concept 2

This concept necessitates higher initial investment costs due to the expensive photoelectric sensors, electric screwdriver with multiple heads, fail-safe structure, multiple fire agents, and the data acquisition system with a multi-battery measurement fixture, resulting in a negative evaluation for low initial costs (-). Additionally, the inspection sensors, fail-safe structure, and data acquisition system require a constant power supply, and the hand tool drill needs regular charging and eventual battery replacement, leading to a negative evaluation for low resource costs (-). Regarding operation costs, the reliance on human labor and electricity for a few devices leads to a neutral assessment (o). The innovative structural design, aimed at optimizing functionality, requires extensive development time to tailor fixtures for batch-size pre-tests and general grip function during disassembly. This design must allow access to all key spots, such as terminals and screw locations while ensuring a secure fit. Furthermore, the fail-safe box must effectively isolate hazards without impeding functionality, contributing to a lengthy development period, which is assigned a strongly negative evaluation (- -). The usage of sensors, the data acquisition system, and the fail-safe structure necessitate calibration, resulting in a slightly negative evaluation for a short calibration time (-). However, these innovative fixtures and techniques enable the processing of multiple items simultaneously, such as batch pre-tests and the removal of multiple screws at once, leading to a positive evaluation for short operation time (+). Additionally, the specifically designed fixtures error-proof the process, eliminating human error by allowing only correct operability, achieving a high level of process simplicity (++). Conversely, the highly tailored process results in unsatisfactory process flexibility, as adapting to other battery types and overall process changes is difficult (- -). The concept also provides physical protection for the operator through the fail-safe box structure and the use of respiratory and rubber glove PPE. This targets SPTF No. 1, 2, 4, 7, and 8, and mitigates No. 3 and 5 through effective workstation design. Thus, the concept yields a satisfactory fulfillment of high SPTF risk mitigation (+). **Result: 2**

Concept 3

This concept aims for automated operations regardless of cost or time efforts. Due to the robotic appliances such as screw removal and grip functions, laser cutter, and smothering equipment, the initial investment costs are extremely high and assigned a strongly negative evaluation (- -). All this equipment requires electricity, and the smothering substance must be refilled after use, resulting in a negative evaluation for low resource costs (-). Operation costs are similarly high due to ongoing power supply, regular maintenance, and machine downtime, leading to unsatisfactory operational costs (-). Development time is rated neutral (o), as robots are available for purchase, but the optical inspection and data acquisition require further development. The calibration time is extensive, as all techniques must be adapted for RCB disassembly, including training machine learning algorithms for optical inspection, precise setup of robots, and calibration of the laser cutter and data acquisition process, resulting in a strongly negative evaluation (- -). However, this extensive calibration ensures smooth, quick processing of RCBs, leading to a very short operation time (++). The robotic appliances simplify the process for human operators, who take on control responsibilities, thus resulting in a positive evaluation for process simplicity (+). However, process flexibility is limited due to the precise calibration required for the specific RCB disassembly, resulting in a negative evaluation for high process flexibility (-). The process is not intuitive, but human involvement is minimal, leading to a highly satisfactory level of SPTF risk mitigation (++). **Result: 6**

Concept 4

Concept 4 is a compromise between inexpensive options and selected tools that enhance the process concerning operation time. Thus, concept 4 represents the compromise concept with a majority of the concept 1 design solution with selected alternatives to improve the process time. Therefore, a hand tool drill and a wire cutter are utilized instead of a set of manual screwdrivers and a utility knife which leads to increased initial investment costs compared to concept one, and it is assigned a neutral (o) value. Due to the hand tool drill operation, at some point, the drill must be recharged, and the batteries replaced, which results in a neutral evaluation of the low resource criterion. Otherwise, this approach does not yield significant operation costs, similar to concept 1, and is assigned a plus (+) as well. Similarly for the development time (+) and the short calibration time (++). In terms of the operation time however, this concept employs hand tool drills and wire cutters which allow for a quicker and more precise fulfillment of tasks and therefore a considerable improvement in comparison to concept 1 (+). The wire cutter eases the cut operation through the handle leverage and raises the process simplicity (+). The remaining two criteria of process flexibility and SPTF risk mitigation are evaluated in the same way as concept 1 (+). **Result: 13**

Upon assignment of the values recorded in Table 7, following a methodological approach and systematic justification, concept 4 emerges as the most suitable for the RCB disassembly and is thereby selected.

Appendix E – Glovebox Design

To raise the feasibility and probability of application of the created safe, manual RCB disassembly approach, a first glovebox prototype is designed using inexpensive materials to provide an enclosed hazardous battery disassembly space. As a full elaborate design according to standards such as VDI 2221-1 exceeds the scope of this master's thesis, the prototype is created by following an intuitive approach. This first structural prototype serves as a foundation for future elaborate product design, adaptations, and iterative design circles. For that, the sections of necessary parts, material, dimensions, and types of connection are elaborated.

Necessary Functions and Structures

To fulfill the function of the glovebox as outlined in the body of this thesis, this box necessitates a large space to accommodate small waste storage areas and a main working area. Furthermore, the RCBs must be inserted into the box and the extracted modules removed from the box, as well as the additional plastic and electronic parts that are assigned for recycling. It should be possible to access, insert, or remove, all components of the system without the need for the operator to withdraw their hands from the glovebox. The most important part is the physical separation of the disassembly process from the operator and establishing a reasonably sealed space, if all doors are closed. Additionally, the operator must be capable of observing internal processes through a window.

Lastly, it is imperative that the glovebox not disintegrate or otherwise fail during operation.

Necessary Parts

This glovebox comprises a closed volume, into which an operator can stretch his arms through rubber gloves. These rubber gloves also serve as a layer of electrical insulation. One option is to obtain sufficiently long gloves that provide an electrical insulation layer, heat protection, and chemical resistance. A combination of all three in addition to the length requirement results in considerable costs. The alternative is to utilize a combination of a flame-resistant long sleeve and have the operator insert chemically resistant gloved hands or attach the gloves to the separate sleeve. To achieve a minimal cost option, the combination of a sleeve and rubber gloves is selected. This also accommodates the possibility to only replace the gloves and reuse the sleeves if the gloves must be substituted. Research yields that glove sleeves add electrical protection. To observe internal processes, a transparent window must be implemented. The ideal position of the window is in the operator's cone of vision without unergonomic postures or body movements, on which further information can be obtained in the works of Schlick, Bruder, and Luczak [87] or in the standards prescribing ergonomic workplace design. One possible position is at the top surface of the glovebox. In addition, the battery packs need to be inserted into the glovebox, which requires an input location with a closeable door and a separate output location with a respective closeable door.

Dimensions

The inserted battery does not exceed the volume of W x L x H: 10 cm x 15 cm x 15 cm, and the extracted battery module 7 cm x 10 cm x 6 cm. These values reflect the largest dimensions of the inserted DEWALT RCB and the height of the extracted DEWALT battery module of six cells. These are the limitations for the insertion and removal door but also influence the minimal working space. To facilitate the ergonomic design of the two holes for the hands, the findings of the Association of German Engineers are consulted. According to them, the preferred area of both hand's operation is approximately one shoulder width apart, with a typical range of 40 – 53 cm independent of gender [88,89]. It can be deduced that for an ergonomic approach, the center point of the glove holes must be separated by at least 30 cm, provided that the elbows are angled outside of the box and the hands approach each other within the box. According to the standard ISO/TR 7250-2, the hand is 10-12 cm wide on average, with the forearm being larger [89]. These anthropometric measurements restrict the minimal size of the holes, leading to a hole diameter of ideally 15 cm. Also, repositories for electronic waste, plastic waste, and sand storage must be allocated inside, leading to another at least 10 cm required in depth.

Material

The material requirement is that it must be easily obtainable, such as wood or particle board. Furthermore, both represent sustainable solutions as particularly particle board is manufactured of waste material and therefore, cheaper. **Attachment methods** have been assessed with regard to sustainability, load limits, safety of connection, and availability. Wood glue is the first association to attach pieces of particle board. However, it either does not adhere well or it represents a non-destructively detachable connection. It also has the disadvantages of potentially not sealing well and it can only bear limited loads as the area of application is significantly limited to the minimal thickness of particle board. Thus, in case of an explosion, the generated energy could rupture the connection, or if unintentionally hit, the box would fall apart. Screws on the other hand have the advantage of being a reversible attachment type, which can be removed and reused, enhancing sustainability. Squared wooden profiles can be utilized to facilitate solid material to fasten the screws, as the particle board does not provide enough material or grip.

Prototype Concept

All these limitations result in a first draft of a 60 cm wide, 50 cm deep and 32-40 cm high (slanted top cover) glovebox, of which a first sketch is visualized in Figure 15. Furthermore, simple sliding doors within grooves in wooden profiles to the left and right are chosen for the prototype to later identify potential optimization potential for the insertion and extraction doors. The profiles also serve as solid volume into which the screws can be tightened to fix the chipboard walls and attach all walls. Thus, there is at least one cube of wood attached on all edges to provide fastening material. Moreover, an acrylic window is chosen to fulfill the observation task. The following Table 11 provides an overview of approximate items that can be used to create the glovebox prototype, of which a first model is illustrated in Figure 16. However, these are only examples of products and can be substituted by similar items and supplemented by other objects.

Table 11: Overview of items required for the glovebox prototype, all links were last accessed on 06/24/2024

Item	Size	Q	Total Cost	Source
Rubber Sleeves	18 in	1	8.3 USD	Global Industrial https://www.globalindustrial.com/p/ironcat-irontex-flame-retardant-cotton-sleeves-green-18-all-cotton-B1030724?referer=L2Mvc2FmZXR5L3BlcnNvbmFsX3Byb3RlY3RpdmVfZXF1aXBtZW50L2dsb3Zlc19zbGVldmVzL2FybV9wcm90ZWN0aW9uX3NsZWV2ZXNfYmlicw%3D%3D&prindex=0&pgkey=32225
Rubber Gloves	13 in	1	1.9 USD	Global Industrial https://www.globalindustrial.com/p/flock-lined-x-large-nitrile-glove-18-mil-size-10?referer=L2Mvc2FmZXR5L3BlcnNvbmFsX3Byb3RlY3RpdmVfZXF1aXBtZW50L2dsb3Zlc19zbGVldmVzL2NoZW1pY2FsX3Jlc2lzdGFudF9nbG92ZXM%3D&prindex=0&pgkey=28502
Acryl Glass	18 in x 24 in x ¼ in	1	35 USD	Home Depot https://www.homedepot.com/p/OPTIX-18-in-x-24-in-x-0-220-1-4-in-Clear-Acrylic-Sheet-MC-21/202038050

Chipboard	≈ 2 m^2	1	14 USD	Home Depot https://www.homedepot.com/p/Hardboard-Tempered-Panel-Common-1-8-in-4-ft-x-8-ft-Actual-0-115-in-x-47-7-in-x-95-7-in-832777/202189720
Wooden Square Bar	1 in x 1 in x 36 in	7	32.2 USD	Home Depot https://www.homedepot.com/p/Kelleher-1-in-x-1-in-x-36-in-Wood-Square-Dowel-IM8316U-8/329049488
Phillips Wood Screws	¾ in	24	8 USD	Home Depot https://www.homedepot.com/p/Everbilt-8-x-3-4-in-Phillips-Flat-Head-Zinc-Plated-Wood-Screw-100-Pack-801812/204275494

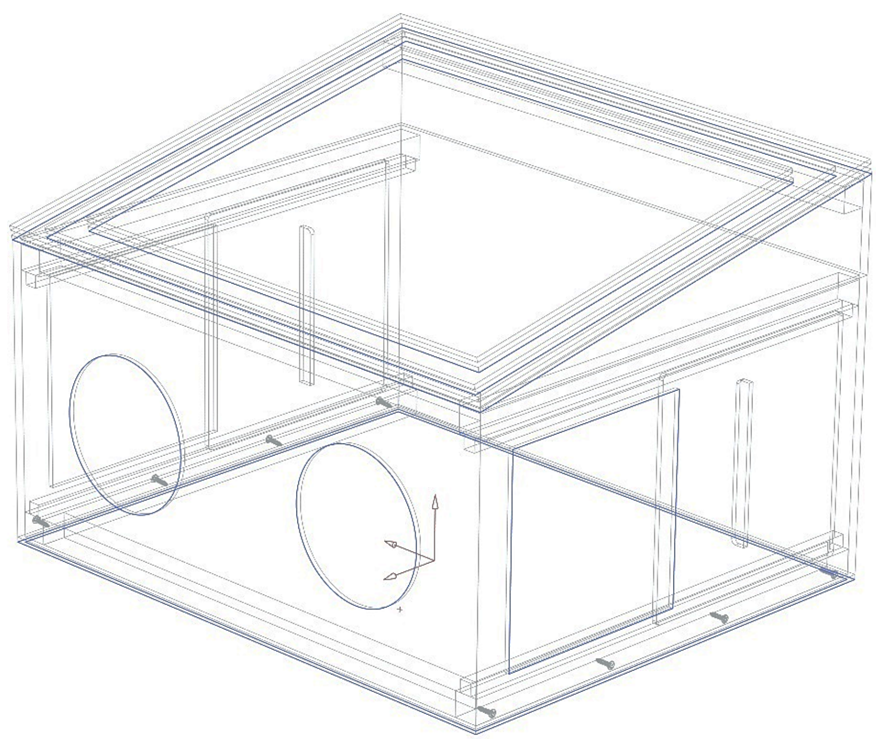

Figure 15: Sketch of the structure of the glovebox prototype with exemplary, illustrative components

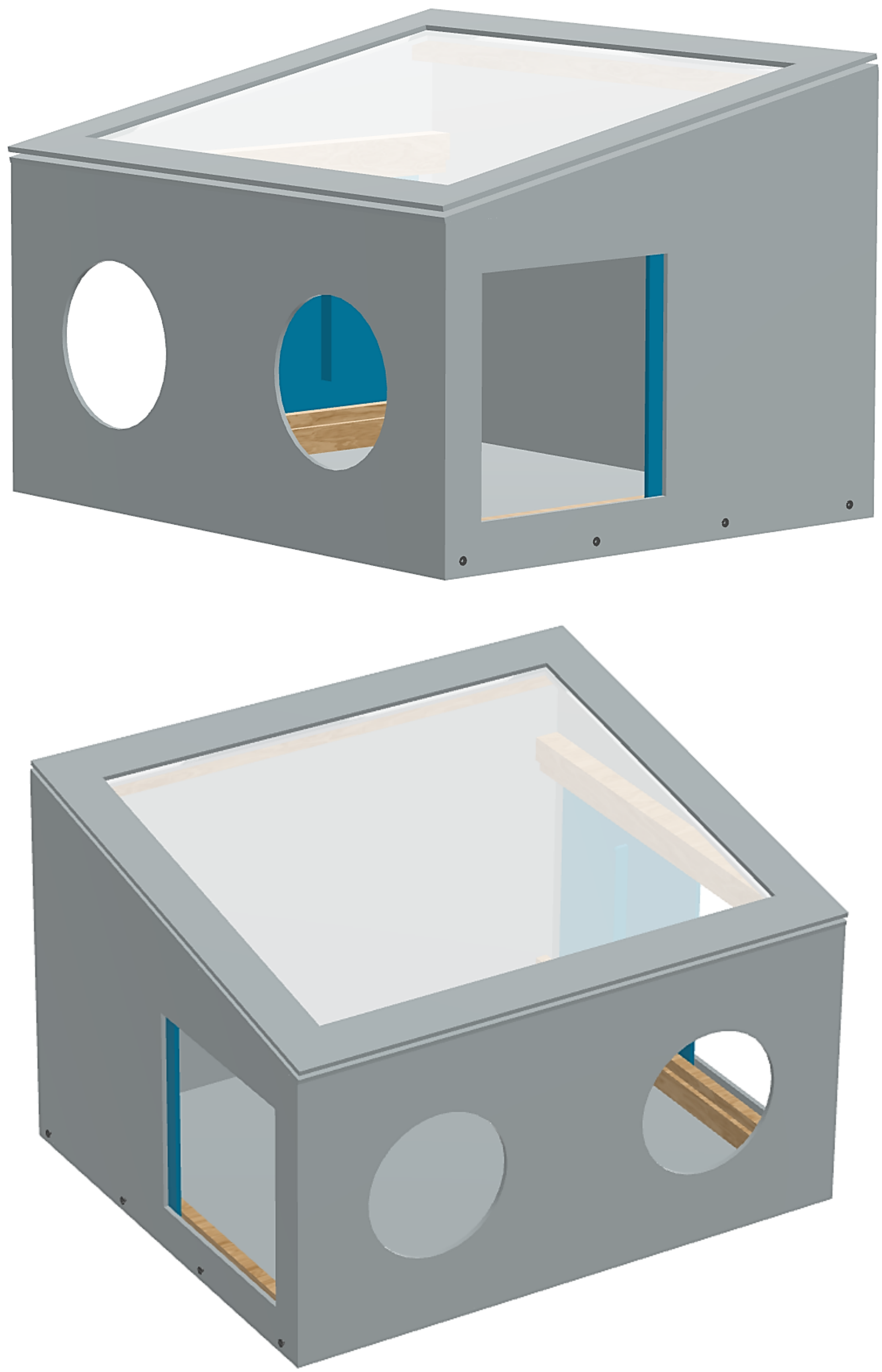

Figure 16: Glovebox prototype model with exemplary, illustrative components, such as sliding doors in blue, wooden square bars, and a translucent window

Appendix F – Sources for Disassembly Workstation Equipment

The following table serves as a supplement to Table 9. All sources have been last accessed on 06/24/2024.

Table 12: Sources for disassembly workstation equipment items

Item	Cost per item	Source
Multimeter	20 USD	Harbor Freight https://www.harborfreight.com/dm300-pocket-sized-digital-multimeter-64018.html?utm_source=bing&utm_medium=cpc&utm_campaign=425671834&campaignid=425671834&utm_content=1168781886897645&adsetid=1168781886897645&product=64018&store=
Spare battery (LR44)	0.3 USD	Amazon https://www.amazon.com/LiCB-Pack-Battery-Button-Batteries/dp/B075B3LB8K/ref=sr_1_6?dib=eyJ2IjoiMSJ9.Qvsr_QDwWVSuWQGSzMAZKcgpGwlQftIgLBjfHk3oSteGe40wwwKIdjza92UWTtQfRJnKb4_XS9UYmPnJz_NGFYs-TDGxgoU-RNh1YoMKdscL0PEbg8r8sPD89RYB9Rpz7G1QPRiNRzStW6PQ9bmGoG37Gtl-sDuHMAccIIlUvuTXCOpGkKrPWTG2eOOc31BMa_rMew3Oh62-Z4KK3qBHJ5i0XJID6kuMMSloYsz1-GdmJmK830c1g9KbtrsLN43STxGBrdadfpPq0b3rEOR96K1NSnyf_A5iguoyOnO8oFw.zHshJRQZx4YHYUKj5SOiUcyDKa1Bb-hpVad_9_86Qg0&dib_tag=se&keywords=lr44+battery&qid=1718987222&sr=8-6
Repository	1.4 USD	Global Industrial https://www.globalindustrial.com/p/global-stacking-bin-4-1-8x7-3-8x3-blue

Hand tool drill	20 USD	Habor Freight https://www.harborfreight.com/power-tools/drills-drivers/12v-cordless-38-in-drilldriver-kit-57366.html
Bit Set	10 USD	Habor Freight https://www.harborfreight.com/security-bit-set-with-case-100-piece-68457.html
Drill bit extension	9.0 USD	Habor Freight https://www.harborfreight.com/impact-rated-6-in-magnetic-bit-holder-64766.html
Wire cutter	2.8 USD	Habor Freight https://www.harborfreight.com/4-12-in-diagonal-cutters-63814.html
Sand, 2 kg	0	-
Rubber sheet	18 USD	Rubber Sheet Warehouse https://rubbersheetwarehouse.com/products/silicone-rubber-rolls-60a-medium-hardness?variant=31238759055415
Grounding Cable	14.1 USD	MRO Essentials https://mroessentials.com/products/static-care-esd-grounding-cable-with-alligator-clip-8-long-with-banana-jack-outlet-plug-adapter-ground-garments-and-mats-with-alligator-clip?variant=42864003023016
Rubber gloves, pair	1.9 USD	Global Industrial https://www.globalindustrial.com/p/flock-lined-x-large-nitrile-glove-18-mil-size-10?referer=L2Mvc2FmZXR5L3BlcnNvbmFsX3Byb3RlY3RpdmVfZXF1aXBtZW50L2dsb3Zlc19zbGVldmVzL2NoZW1pY2FsX3Jlc2lzdGFudF9nbG92ZXM%3D&prindex=0&pgkey=28502

To balance the process line, the process time of workstation equals the number of operators per workstation needed. Each larger rectangle in Figure 17 represents one operator, while at workstation 4 one operator can process five RCBs simultaneously, resulting in a process time of 1 RCB/min and eight operators.

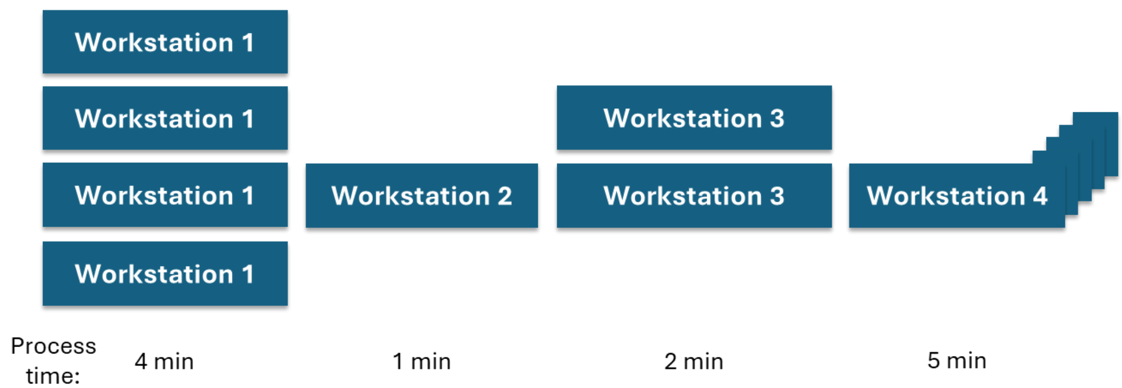

Figure 17: Process line balancing according to estimated process times

In the following, all prerequisites to the calculation are displayed and all "cells" refer to 18650-type LIB cells, which is the cell encountered in three of four disassembled RCBs and therefore is utilized as a foundation for the estimation.

Assumptions:

- 8 operators/day per process line
- Minimum wage 14 USD/h (for Rhode Island) [90]
- Workday of 8 h/day
- Process time: 60 RCBs/h
- Downtime: 0.5 h/day
- Initial equipment costs: 210 USD (see Chapter 5.4)

- Batteries: 5 cells/RCB

  85 % recycling, only 0.59 USD/cell [73]

  10 % lower-quality remanufacturing, 0.59 USD/cell plus additional 2 USD/RCB [74]

  5 % higher-quality remanufacturing, 0.59 USD/cell plus additional 3 USD/RCB [74]

Batteries per day: (60 RCBs/h * (8 – 0.5 h/day) = 450 RCBs/day

Batteries per hour: 450 (RCBs/day) / (8 h/day) = 56 RCBs/h

Disassembly Cost per day:

((14 USD/(h * operator)) * 8 operators) / (56 RCBs/h) = 2 USD/RCB

450 RCBs/day * 2 USD/RCB = 900 USD/day

Revenue: 450 RCBs/day * 5 cells/RCB * 0.59 USD/cell

+ 450 RCBs/day * 0.1 * 2 USD/RCB + 450 RCBs/day * 0.05 * 3 USD/RCB

= 1,327.5 USD/day + 90 USD/day + 67.5 USD/day = 1,485 USD/day

Revenue, worst case: **(**all RCBs categorized into recycling)

450 RCBs/day * 5 cells/RCB * 0.59 USD/cell = 1,327.5 USD/day

Profit: (revenue – costs =) 1,485 USD/day – 900 USD/day = 585 USD/day

Profit, worst case: (only material resale value)

1,327.5 USD/day – 900 USD/day = 427.5 USD/day

Hence, for a processing time of 1 minute per effective battery disassembly, the achievable profit is estimated at 585 USD per day, not including facility or subsidiary costs for infrastructure, managers, supervisors, or patents and rights. Furthermore, this estimation does not include considerations on the uptime of devices such as the multimeter, the electric screwdriver, or the SOH equipment, delays of any kind, nor fixed costs of the facility such as infrastructure, electricity, rent, or the extensive costs for the SOH equipment. A profound, comprehensive analysis of the economic situation of this concept is beyond the scope of this master's thesis and therefore it is not further detailed.

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