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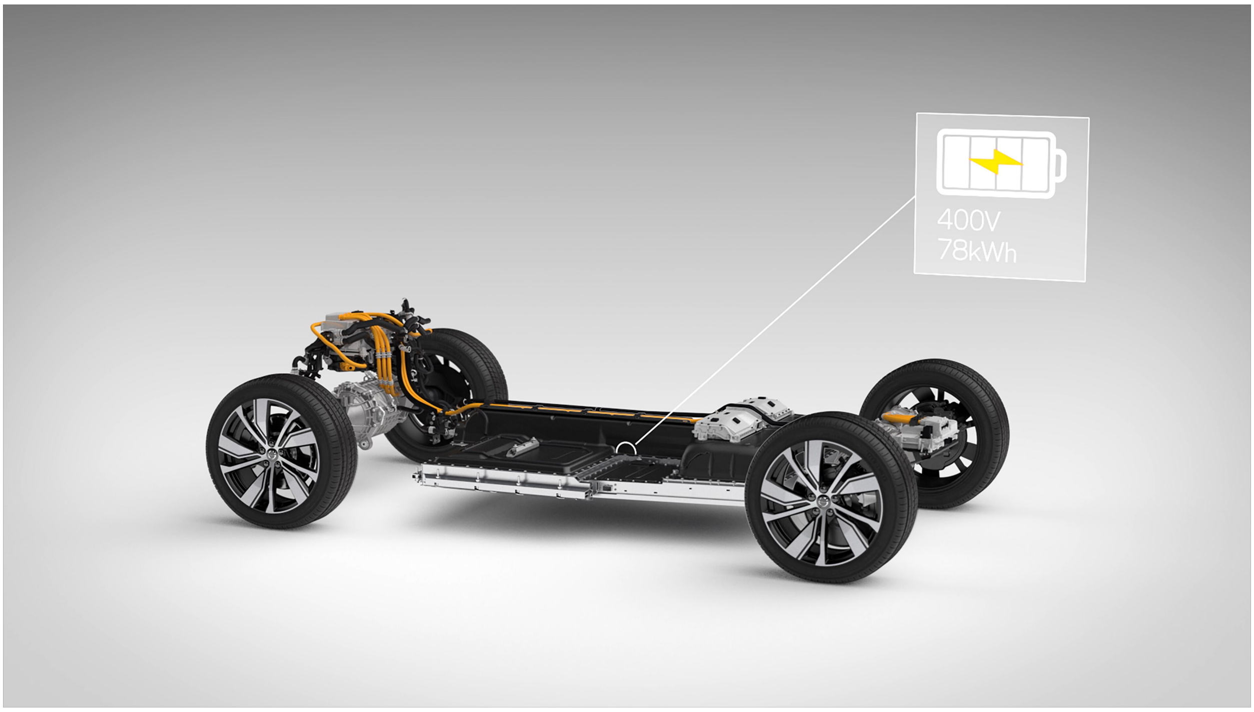

Improving circularity for electric vehicles through repair

A techno-economic analysis of a BEV HV battery and its climate impact

Master's thesis in Industrial Ecology

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Cover: XC40 Recharge Battery Package, from Volvo Cars Content Store.

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Abstract

The current climate crisis is a huge threat to our planet and the changes we implement within the upcoming years will decide how well we can mitigate its most severe effects. As the transport sector alone makes up about 12% of global annual carbon dioxide (CO_2) emissions, one of the key solutions that has been pointed out is the electrification of the vehicle fleet.

Volvo Cars, a premium car brand with its headquarters in Gothenburg, have committed to a fully electrified portfolio in 2030. Battery electric vehicles (BEVs), however, do not come without environmental problems. The manufacturing of lithium-ion battery cells requires significant amounts of energy and is known to have destructive social and environmental impact. In order to reduce the impact, a circular approach for electric vehicle materials needs to be implemented. One way this can be enabled, is by repairing faulty lithium-ion batteries. This thesis aims to investigate and quantify the CO_2 emissions generated by the manufacturing and transports of a lithium-ion battery as well as the potential savings gained through the repair process. In addition to this, the costs of the repair have been investigated to add a financial perspective. Existing data from literature and environmental databases have been used to quantify the emissions and then, by constructing a decision support tool, investigate the emissions and costs from the repair. This in order to show the potential savings in CO_2 emissions and and costs.

The quantification of the manufacturing related emissions for the specific battery pack under investigation resulted in a total of 11 tonnes of CO_2e. According to this study, the repair of the specific lithium-ion battery under investigation can result in as much as 99% savings for CO_2 and cost compared to producing a new pack. The study also shows that there are significant differences in CO_2 savings between the investigated scenarios, where the maximum scenario is over 300 times larger than the minimum scenario. The transports generally make up a relatively small share of the total emissions in the studied scenarios and are deemed to have small influence. As a future outlook, the consequences of developing non-repairable BEV batteries have been highlighted together with a comparison of a centralized and decentralized repair strategy. In order to build and increase knowledge of EV circularity, it will be crucial for Volvo Cars to continuously investigate the climate impact for all BEV battery components to identify action areas. This thesis has been carried out at Chalmers University of Technology in collaboration with Volvo Cars.

Keywords: battery electric vehicle, BEV, EV, high voltage battery, lithium-ion, climate impact, circular economy, repair, life cycle assessment, end-of-life.

Acknowledgements

This thesis was conducted during the spring of 2022 as part of the master program in Industrial Ecology at Chalmers University of Technology. It was done at the division of Environmental Systems Analysis in collaboration with Volvo Cars.

First, we would like to thank our supervisor at Chalmers, Anders Nordelöf, for all the support, feedback and valuable discussions during this spring. We are constantly inspired by how you manage to combine your knowledge and strong skills in the field with a down-to-earth attitude and good sense of humor. It's been a pleasure to work with you. Additionally, we would like to thank our examiner, Björn Sandén.

Secondly, we would like thank our supervisor at Volvo Cars, Aivis Liepins, along with the entire team at Battery Lifecycle Services. Thanks for welcoming us to the team, inviting us to social gatherings, sharing your knowledge and providing us with valuable help and support throughout the whole process.

We would furthermore like to like to thank our fellow Chalmerists for bringing positivity, good spirit and being great discussion partners when needed. Finally, we would like to thank our friends and family for their continuous support throughout our studies.

Alice Granehed & Jacob Lövstedt, Gothenburg, June 2022

To Jacob: *Partner in crime! Can't believe 6 months passed that quickly. Incredibly happy I got to spend them with you and conduct this work together. Always so supportive and uplifting, these months would've not been the same without you. Thank you for being you.*

Alice Granehed

To Alice: *Thank you for all the memories, laughs and for always challenging me. You are a true inspiration and source of joy to everyone around you, never change who you are! I will miss working with you and I wish you all the best for the future!*

Jacob Lövstedt

Contents

List of Acronyms

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

APAC	Asia-Pacific
BEV	Battery Electric Vehicle
BMB	Battery Management Board
BMS	Battery Management System
CDC	Central Distribution Center
EF	Emission Factor
EOL	End of Life
EMEA	Europe, the Middle East and Africa
EV	Electric Vehicle
GHG	Greenhouse Gas
GOT	Gothenburg
HEV	Hybrid Electric Vehicle
HV	High Voltage
IBIS	Integrated Battery Interface System
ICE	Internal Combustion Engine
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LDC	Local Distribution Center
LIB	Lithium-ion Battery
LTL	Less Than Truckload
NMC	Lithium Nickel Manganese Cobalt Battery
PHEV	Plug-in hybrid electric vehicle
SHG	Shanghai
SOC	State of Charge
SOH	State of Health
VCD	Volvo Cars Dollar

Nomenclature

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

Parameters

$C_{battery\ pack}$	Cost of changing one battery pack	[VCD]
$C_{carrier}$	Cost of changing one carrier	[VCD]
$C_{CDC-LDC}$	Cost of transporting one battery pack from the CDC to an LDC	[VCD]
$C_{last\ mile\ Nordics}$	Cost of transporting one battery pack from an LDC in the Nordics to a workshop (Last mile delivery)	[VCD]
$C_{last\ mile\ rest\ of\ EU}$	Cost of transporting one battery pack from an LDC in the rest of the EU to a workshop (Last mile delivery)	[VCD]
C_{module}	Cost of changing changing one module	[VCD]
$C_{module\ electronics}$	Cost of changing one module electronic unit	[VCD]
$C_{pack\ electronics}$	Cost of changing one pack electronic unit	[VCD]
$C_{per\ km}$	Total cost to repair one battery pack per km	[VCD/km]
$C_{SHG-GOT}$	Transport cost from Shanghai to Gothenburg	[VCD/dm^3]
$C_{supplier-SHG}$	Cost of transporting one battery pack from a supplier in China to Shanghai	[VCD/dm^3]
$C_{technician}$	Labour cost for battery center technician	[VCD/hour]
$CO_{2,per\ km}$	Total emissions to repair one battery pack per km	[kg CO_2e/km]
$d_{CDC-LDC}$	Transport distance from the CDC to the respective LDCs	[km]
$d_{Ghent-LDC}$	Transport distance from Ghent to the respective LDCs	[km]
$d_{last\ mile}$	Last mile delivery distance from LDC to workshop	[km]
$d_{lifetime}$	Lifetime of battery pack	[km]

$d_{mileage}$	Driven distance (mileage)	[km]
$d_{SHG-GOT}$	Transport distance from Shanghai to Gothenburg	[km]
$d_{supplier-SHG}$	Transport distance from supplier in China to Shanghai	[km]
$E_{Al,extrusion}$	Emissions for aluminium extrusion	[kg CO_2/kg]
$E_{Al,milling}$	Emissions for aluminium milling	[kg CO_2/kg]
$E_{Al,production}$	Emissions for aluminium production	[kg CO_2/kg]
$E_{all\ modules}$	Emissions for all modules	[kg CO_2e]
E_{BMB}	Emissions for one BMB	[kg CO_2e]
$E_{carrier}$	Emissions for the carrier	[kg CO_2e]
E_{IBIS}	Emissions for one IBIS	[kg CO_2e]
E_{module}	Emissions for one module	[kg CO_2e]
$E_{module\ electronics}$	Emissions for the module electronics	[kg CO_2e]
$E_{pack\ electronics}$	Emissions for the pack electronics	[kg CO_2e]
E_{rest}	Emissions for remaining components	[kg CO_2e]
$E_{rest,Ellingsen}$	Emissions for remaining components in the study by Ellingsen	[kg CO_2e]
$E_{transport,used\ pack}$	Emissions for transporting one used battery pack	[kg CO_2e]
$E_{transport,new\ pack}$	Emissions for transporting one used battery pack	[kg CO_2e]
$E_{transport,\ spare\ parts}$	Emissions from transport of spare parts	[kg CO_2e]
$EF_{truck,APAC}$	Emissions factor for truck transport in APAC	[g CO_2e/tkm]
$EF_{truck,EMEA}$	Emissions factor for truck transport in EMEA	[g CO_2e/tkm]
EF_{ship}	Emissions factor for truck transport	[g CO_2e/tkm]
$m_{battery\ pack}$	Weight of one battery pack	[kg]
$m_{carrier}$	Weight of carrier	[kg]
m_{module}	Weight of one module	[kg]
$m_{module\ electronics}$	Weight of module electronics	[kg]
$m_{pack\ electronics}$	Weight of the pack electronics	[kg]
m_{rest}	Weight of remaining components	[kg]
$m_{rest,Ellingsen}$	Weight of remaining components in the Ellingsen study	[kg]
$m_{rest,Volvo\ Cars}$	Weight of remaining components for the Volvo Cars battery	[kg]
$t_{carrier}$	Time to repair carrier	[hours]
t_{module}	Time to repair one module	[hours]

$t_{module\ electronics}$	Time to repair one module electronic unit	[hours]
$t_{pack\ electronics}$	Time to repair one pack electronic unit	[hours]
$v_{components}$	Volume per component	[m^3]
$\sum C_{repair}$	Total cost of repairing one battery	[VCD]
$\sum C_{repair,\ battery}$	Sum of all costs to repair one battery, excluding transport	[VCD]
$\sum C_{repair,\ transport}$	Sum of all transport costs	[VCD]
$\sum CO_{2,battery\ pack}$	Sum of all component emissions for a battery pack	[kg CO_2e]
$\sum CO_{2,common}$	Sum of all emissions for repair scenario common	[kg CO_2e]
$\sum CO_{2,new\ battery}$	Sum of all emissions for one new battery	[kg CO_2e]
$\sum CO_{2,repair}$	Sum of all emissions for one repair scenario	[kg CO_2e]
$\sum CO_{2,transport,new\ battery}$	Sum of all transport emissions from a new battery	[kg CO_2e]
$\sum CO_{2,transport,repair}$	Sum of all transport emissions from a battery to be repaired	[kg CO_2e]

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1
Introduction

1.1 Background

Our world and our climate is changing. We are at the point where we, directly or indirectly, are reminded of climate change and its effect on our society on a daily basis. In the past few years only, we've experienced major climate events including record high temperatures, melting of the polar ice caps, wildfires, intense droughts and storms worldwide, only to name a few. The pressure on our society to decrease emissions of greenhouse gases (GHGs) and keep the average global temperature increase well below 2°C above pre-industrial[1] levels, 1,5°C in the optimal case, is immense (The UN, 2015).

A major contributor to this warming effect is the GHG carbon dioxide (CO_2), which is generated mostly by anthropocentric activities. As it traps heat from the sun's radiation within the atmosphere, it contributes to increasing temperatures over time. It furthermore remains in the climate system for a long time after being emitted, leading to that CO_2 emissions cause increases in atmospheric concentrations that will last thousands of years (NASA, 2022). As of right now, we are emitting CO_2 at a rate not previously observed. In fact, about half of cumulative anthropogenic CO_2 emissions between 1750 and 2010 have occurred in the last 40 years. In 1970, cumulative anthropogenic CO_2 emissions from fossil fuel combustion and industrial production since the pre-industrial era were 420 gigatons (Gt) of CO_2e and in 2010, that number had tripled to 1 300 GtCO_2e (IPCC et al., 2014).

The need to decarbonize the society in order to mitigate the most severe effects of climate change has shone a light on the automotive industry, both in terms of driving climate change but also to potentially mitigating it. Electrification of the vehicle fleet, being the transformation from the combustion engine vehicle to the plug-in electric, has been pointed out as a core solution to decrease emissions and mitigating climate change. This has inevitably led to an increasing demand of electric vehicles on the global market and has put pressure on the industry to transform (Carriquiry, 2020). Battery electric vehicles, or BEVs, are fully electric vehicles with a plug-in charging solution. Common main BEV components are, a high-voltage (HV) battery, one or multiple electric motors and a controller to

[1] before year 1750

manage the power electronics (Nieuwenhuis et al., 2020). The superior BEV HV battery technology on the market today is the lithium-ion (Li-ion) battery, or LIB. A main challenge associated with the production of LIBs is the strong dependence on some specific scarce resources. Naturally, producing a LIB requires lithium but multiple other minerals such as nickel, manganese and cobalt are also required. An issue regarding these minerals are that few extraction locations exist which come with extensive social, economic and environmental impacts (Nealer & Hendrickson, 2015).

Looking to the environmental impact of LIBs for vehicle applications, several life cycle assessment studies have been conducted. The use phase[2] of a LIB is commonly pointed out as clean, due to no tail pipe emissions from the vehicle. However, the environmental load of the use phase depends on the electricity generation mix used for charging the vehicle, in particular the level of fossil fuel sources in the mix. Emissions from charging are only zero if the electricity is sourced from 100% renewable energy. Some studies even highlight the use phase as the one with more environmental impact. On the other hand, the manufacturing phase[3] is in itself an energy intense process where impact could effectively be reduced by reusing and recycling of materials and battery components. The views on which are the key drivers of environmental impact in the life cycle of a LIB, however, are different. Battery EOL and second-life solutions are expected to be positive contributors, that being through prolonging the lifetime of a battery (Nealer & Hendrickson, 2015). As the population of EVs on the market continue to increase, the expansion of EOL management of electric vehicle batteries becomes critical (Carriquiry, 2020). Several circular economy solutions are available today and among these, the key categories are reuse, repair and recycling. A recently proposed legislation in the EU, the *Fit for 55* agenda, sets targets to cut CO_2 emissions from cars by 55% by 2030. The agenda also proposes to completely cut emissions from cars by 2035. In order to achieve these goals, a significant increase in the uptake of electric vehicles will be needed (European Parliament, 2021).

Volvo Car Corporation, commonly Volvo Cars, is a Swedish automotive manufacturer with around 40 000 employees globally and headquarters in Gothenburg, Sweden. It was one of the first premium car brands to commit to a hybrid or full-electric powertrain portfolio. The company aims to be become a fully electric car provider by 2030, i.e. 100% of global sales are to be made up of battery electric vehicles (Volvo Cars, 2021a). Because of the previously mentioned challenges related to the production of Li-ion batteries required for this expansion, actions within the area of battery management are needed. In early February 2022, Volvo Cars and Swedish battery manufacturer Northvolt confirmed their plans to build a new gigascale-factory as a joint venture in connection to Volvo Cars' facilities in Gothenburg (Volvo Cars, 2022f). An up-scaling of LIB production, which is needed to meet the increasing BEV demand, is expected to have a positive effect in terms of emission reduction and a lower demand of energy per kWh of battery cell storage capacity. Compared

[2]The phase when a product is in use, in this case when the battery is used to power a vehicle
[3]The phase from raw material extraction to when the battery is manufactured and assembled

to a mega-scale factory production, a giga-scale factory could emit up to 45% less emissions per kWh of battery cell storage capacity (Chordia et al., 2021).

Today, the manufacturing of the Li-ion battery makes up as much as 29% of the total emissions from the materials production and refining of the two Volvo Cars BEVs currently on the market, namely the C40 and XC40 (Volvo Cars, 2020) (Volvo Cars, 2021b). This shows the importance of a circular approach for LIBs and for increased efforts in end-of-life (EOL) management for Volvo Cars. The department of Battery Lifecycle Services at Volvo Cars works to accomplish this through repair, second-life solutions and recycling of BEV batteries. A battery center was recently inaugurated at the premises of Volvo Cars in Gothenburg which handles repairs of BEV and PHEV batteries from the Europe, Middle East and Africa (EMEA) markets. The battery center and the processes conducted there will be central to this thesis.

1.2 Aim

With that background, the aim of this thesis is to identify factors in the repair process of a BEV battery pack that generate CO_2 emissions and costs. An additional aim is to show the potential savings, both in terms of CO_2 emissions and costs, of repairing a BEV battery pack in comparison to producing a new pack. This includes identifying and quantifying the generated CO_2 emissions from different activities included in the repair process before comparing with the production of a new battery pack. In addition to this, an aim is also to investigate the potential benefits of developing repairable BEV battery packs, both from an environmental and financial perspective.

The goal is to develop a decision support tool that compares the CO_2 emissions as well as the costs of repairing a battery vs producing a new pack. This tool needs to contain information regarding the emissions and costs from the components as well as the transports. This to provide adequate decision support for Volvo Cars. The indications from such a tool can be used by Volvo Cars to decide when it is environmentally and financially justified to repair a battery pack.

1.3 Research Questions

RQ1: *What are the potential CO_2 and cost savings when repairing a BEV HV battery pack, in comparison to producing a new battery pack?*

RQ2: *What parameter(s), among the studied in this thesis, are the key drivers for CO_2 emissions, and what are the approximate quantities of these emissions, when repairing a BEV HV battery pack?*

1.4 Demarcations

The thesis is limited to HV batteries for BEV applications of the lithium nickel manganese cobalt (NMC) type. The thesis will include environmental carbon footprint and economic cost but no social factors or other environmental factors than climate impact will be considered.

The carbon footprint corresponds to the CO_2 emissions from the manufacturing phase as well as from transports but excludes the use phase of the BEV battery. The economic factors will include the costs of repairing and transporting a BEV battery. As lack of high-resolution data is expected, some components within the pack can be aggregated together and no environmental impacts will in those cases be shown for specific parts. Repairs that need to be performed due to unintended outcomes of the repair process will not be considered.

2

Theory and technical background

2.1 Battery Electric Vehicle

A battery electric vehicle (BEV) is a type of electric vehicle (EV) that has an electric motor as the single source of propulsion. This, in contrast to other EV types such as hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) which utilizes both an electric motor and an internal combustion engine. A common configuration in EVs is to have one electrical motor for the front axle, i.e., front wheel drive (FWD). All wheel drive (AWD) using dual axis drive or a motor within each wheel is also a common option. In figure 2.1, an overview of the main differences between an EV and an internal combustion engine (ICE) vehicle can be seen.

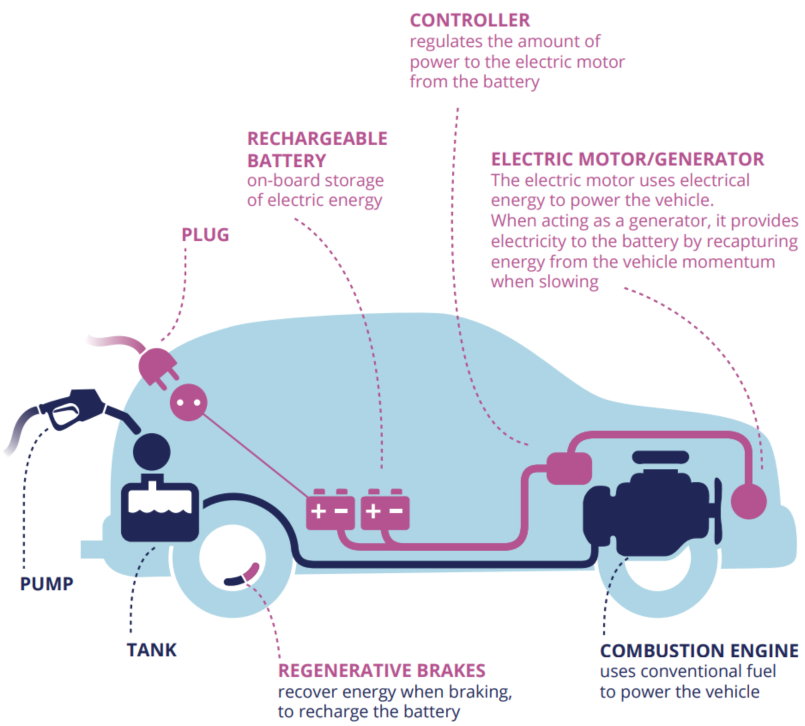

Figure 2.1: Overview of the main differences between a BEV (pink) and a conventional ICE vehicle (blue) (European Environment Agency., 2016).

There are several different ways of charging an electric vehicle, using either alternating current (AC) or direct current (DC). The use of AC (household outlets) requires that the system can convert the electric current from AC to DC, e.g., using an AC/DC converter in order to charge the battery (Un-Noor et al., 2017). SAE International defines different levels for both AC and DC charging, AC is up to 240 V and DC to 1 000 V (SAE International, 2017).

Charge can also be generated through kinetic energy recovery while e.g. braking. However, this is not the primary energy source for the vehicle as it will only provide limited charge and support only during driving. In theory, BEVs do not have any tail pipe emissions during the use phase, in contrast to an ICE, and are therefore often branded as 'clean'. However, this does not provide the full picture as environmental load can be allocated to the use phase of a BEV in the form of potential fossil fuel fractions in the used electricity mix for charging (Nealer & Hendrickson, 2015).

2.1.1 BEV HV battery pack

A BEV battery pack is made up of several hundred battery cells, structured in different configurations and connected together in order to provide power to drive the vehicle. There are different battery cell chemistries where the most prominent in the EV field is the Li-ion chemistry family which has matured as a technology and made significant progress in the last decade (Peters et al., 2017). Within the Li-ion battery family there are several specific chemistries such as Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Iron Phosphate (LFP) and Lithium Nickel Cobalt Aluminum Oxide (NCA). The cells are connected either in series or parallel circuit and some configurations with a mix between parallel and series circuit also exist (Saw et al., 2016). A generic BEV battery can be said to consist of four main parts, namely the battery cells, the battery management system (BMS), the cooling system and packaging. These components together make up a complete *battery pack*. Naturally, within each of these four parts there are several sub-components and the specific configuration of the components vary between different battery manufacturers and chemistries (Ellingsen et al., 2014). A common unit in which to measure the capacity of a BEV battery is kWh of storage capacity, which is the unit that will be utilized throughout this thesis. In figure 2.2, an overview of the components making up a general lithium-ion battery pack can be found. The specific battery of interest for this thesis is described in section 2.1.4.

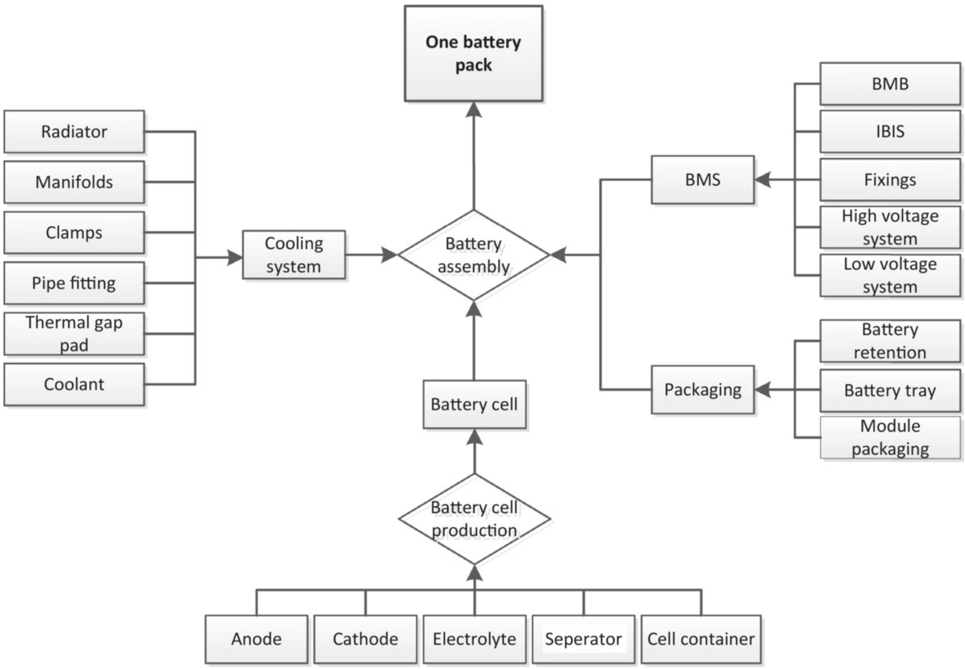

Figure 2.2: Components in a generic lithium-ion battery pack (Ellingsen et al., 2014).

A simplified set-up of a LIB cell is displayed in figure 2.3. A LIB cell's basic function is that energy is created when lithium ions move between the anode and the cathode through an electrolyte. More specifically, during the discharge process, lithium in the anode is ionised and released to the electrolyte. Lithium ions then move through a porous separator and into the lithium metal oxide cathode. Simultaneously, electrons are released from the anode. This becomes electric current travelling to an external load. During the charging cycle, lithium ions move from the cathode to the anode through the separator. Due to this reversible electrochemical reaction, the lithium-ion cells can be recharged (Chen et al., 2012).

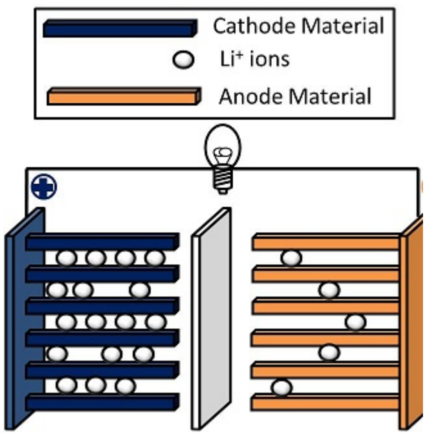

Figure 2.3: Schematic of a Li-ion cell (Materialsgrp, 2010)

The potential voltage of a single LIB cell is usually around 3.6 V. For a full battery pack the potential voltage is 300-600 V, basic energy density is around 110-160 W/kg and the storage capacity commonly above 60 kWh (Chen et al., 2012; Miller, 2015). If the *working voltage*[1] is >60 V (DC) or >30 V (AC), it is classified as a high-voltage battery (UNECE, 2013).

2.1.2 Architecture and integration

There are several ways to integrate a LIB into a vehicle. The two most common ways are either to integrate the battery into the vehicle's floor or to use the transmission tunnel, known as the "T" architecture (Xia et al., 2014). The latter option is more common for PHEVs, while the integration of the battery pack into the floor/chassis is the most dominant for new BEVs. This design allows for more space inside the car and lowers the vehicle's center of gravity. Because the battery need rigorous supports in order to withstand potential impact, the integration and structure of the battery has a significant impact on the safety of the vehicle.

Within the pack, the design can vary as well. In figure 2.4, an overview of two common cell integration approaches, namely module approach and cell-to-pack approach, can be found.

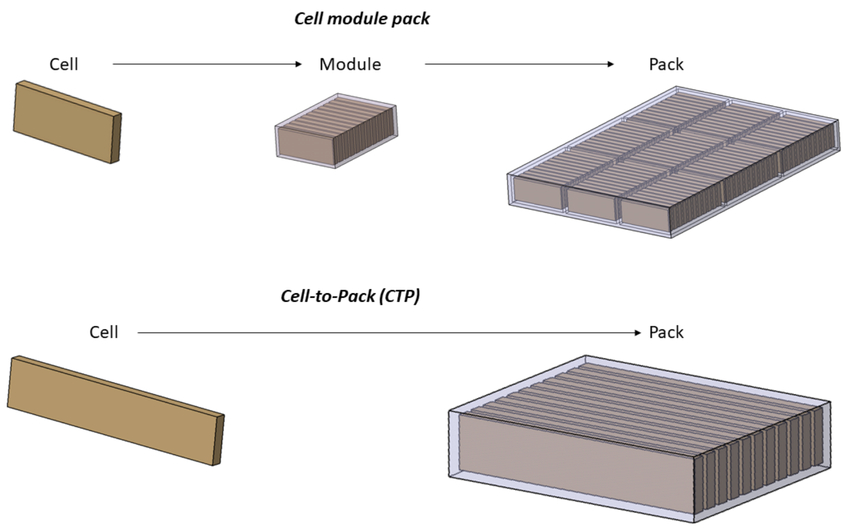

Figure 2.4: Overview of the differences between module approach and cell-to-pack approach.

In the specific battery under investigation, the cells are confined to specific module units and then several modules together are connected to each other and make up the pack (Volvo Cars, 2019). This allows for the possibility to replace cell modules if they break, although a disadvantage of this approach is a lower energy density at pack level due to the less efficient utilization of the volume in the pack (X. G.

[1]highest value of an electrical circuit voltage's root-mean-square

Yang et al., 2021). Another approach is the cell-to-pack architecture where the cells assembles directly into a pack without any modules (X. G. Yang et al., 2021). In the cell-to-pack architecture, the cells are functioning as the structural support of the battery in contrast to the cell-module-pack where the modules constitute the support. This allows for a lower ratio between the specific energy level of the pack to that of the cells as well as a higher volume density in the cell-to-pack architecture (X. G. Yang et al., 2021). A potential benefit of using cell-to-pack vs cell-module-pack is a lower height of the pack, something that is desirable when integrating it into the vehicle (Meng & Zheng, 2020). Using cell-to-pack however limits the ability to replace individual cells and thereby the possibilities to repair the battery. This might result in the need of a complete exchange of the whole pack instead of one or several modules.

2.1.3 Manufacturing of a BEV battery pack

The manufacturing process of a BEV battery pack consists of several steps including: raw material extraction, cell manufacturing (electrode preparation, cell assembly, battery electrochemistry activation), non-cell component manufacturing, integration of cells into modules and assembly of pack (Liu et al., 2021). The cell manufacturing process is commonly pointed out as the process driving the environmental impact, due to several energy-intensive process steps. This is especially true for drying of the electrode and cathode materials which in some cases can account for the majority of the energy consumption in battery pack manufacturing (Yuan et al., 2017). Given the high energy consumption, the electricity mix used at the manufacturing facility have a major effect on the emissions associated with the cell manufacturing. The majority of EV battery cell production today is located in China, Japan and South Korea, all of which are known to have relatively high fossil fuel fractions in their respective electricity mixes (Aichberger & Jungmeier, 2020).

Cell manufacturing in this thesis refers to the three sub-steps: electrode preparation, cell assembly and battery electrochemistry activation, whereas manufacturing in general is used to describe the complete process stated above. Any post-manufacturing transport emissions (e.g., from transport of pack from manufacturer to workshop) is not included in the manufacturing emissions.

2.1.4 The specific battery under investigation

The studied battery is an NMC battery. In figure 2.5, a visual intersection of the studied battery can be found.

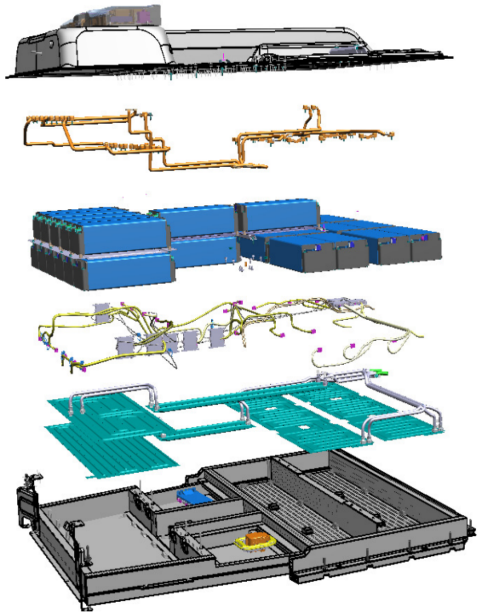

Figure 2.5: The specific battery pack under investigation. From the bottom: carrier, cooling system, electronic system, modules, bus bars & lid (Volvo Cars, 2019).

The battery is integrated into the vehicle using the floor architecture described in section 2.1.2. The battery pack consists of 27 modules where each module consists of 12 cells. These modules, each with a nominal voltage of ∼14.7 V, are connected in series using bus bars, making the total voltage of the battery almost 400 V. The voltage is however dependent on the state of charge (SOC) and can vary between 270 V and 460 V. Total stored energy is 78 kWh while the usable energy is at 75 kWh. The total weight of the battery pack is 500 kg. In addition to the modules the battery consists of several electronic units used to monitor the temperature and cell voltage as well as a main control unit. The modules are attached to a carrier using screw fixings. The modules are furthermore placed on cooling plates which will keep the temperature within an acceptable range.

2.2 Circular economy and battery refurbishing

Circular economy is an economic model based on sharing, leasing, reuse, repair, refurbishment and recycling materials in loops. The system aims to gain the greatest utility and value of products, components and materials at all times and eliminating waste. (The Ellen Macarthur Foundation, 2022). This reduces pressure on natural systems and its finite resources. In contrast to a linear economy, circular economy achieves this by keeping all the resources within the system by for example designing away waste. A change to a circular economy requires a fundamental change within a system when going to a closed loop cradle-to-cradle system (Bocken et al., 2016).

A main challenge on the topic of circular economy for automotive manufacturers is to keep the EV batteries "in the loop" after the first life usage, both to keep an inventory of their respective end locations as well as their state-of-health (SOH) status. SOH for the pack is determined by looking at the capacity of the worst cell in comparison to a new cell. As the recovery options depend on the SOH of the secured battery cells in the pack, keeping track of this information is crucial. In addition to this, the environmental impact and cost of non-recovery have a substantial impact (Cong et al., 2021). The projected price for a battery pack in 2022 is 135 USD/kWh making the price for a 78 kWh battery over USD 10 000 (Edelstein, 2021). Battery refurbishing emerges as a new market and can serve as catalyst for circular economy development. In the field of EV's, it's a promising sustainable business model, promoting end-of-use product treatment through repair, reuse and recycle. The most applicable refurbishing process for a certain type of battery must however be determined by the comparison of environmental aspects and the cost profile (Cong et al., 2021). In figure 2.6, an overview of repair, repurposing and recycling of a BEV battery pack can be found.

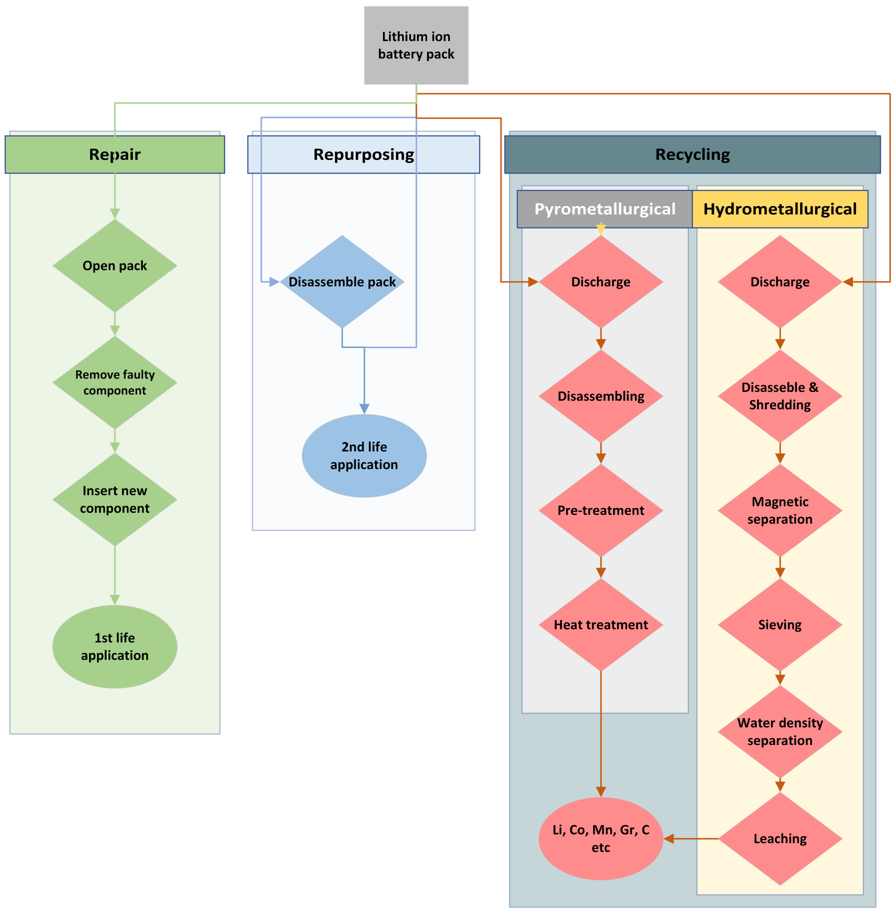

Figure 2.6: Simplified overview of the steps involved in repair, repurposing and recycling of a BEV battery pack

2.2.1 Repair

In the literature of LIBs and end-of-use treatments, it's common to use the term *refurbishment* of batteries. Refurbishment commonly cover the steps: screening, disassembly of pack, repair (cell replacement and refit), reassembly of pack and testing. Repair as a term thus only cover the replacement of cells/modules or other components that have been identified as defective (Aichberger & Jungmeier, 2020). However, at Volvo Cars, the term repair is used instead of refurbishment and therefore holds another meaning than the literature. In this thesis, the definition of *repair* is aligned with that of the literature stating the following:

'An operation where one or several components in the battery pack are replaced in order to bring back the battery to a usable state'

The process starts with the identification of an issue in the BEV battery pack at the dealer workshop. The identification has been done either through analysis of data before opening the pack or by testing the components, modules and/or cells after opening the pack. This is followed by a verification of the electrical circuit. It includes the verification of functioning cables, wiring and connectors. In addition to this, the BMS is tested against certain standards and verified to ensure correct operation and minimize future failures. To finalize the repair, final tests must be carried out to verify that the performance of the battery pack is acceptable (Carriquiry, 2020).

This includes all operations where one or several faulty components are exchanged for functioning ones, although excluding operations where components are mended. This due to the difficulty in gathering and quantifying the emissions related to these activities. Repairing a battery pack can be justified both from an environmental and a financial perspective when one or several components are repaired. The battery then returns to a vehicle application and the full lifetime of the battery pack is enabled (Standridge & Hasan, 2015). In terms of the environmental impact for a BEV battery, where the largest contribution is allocated to the manufacturing phase, a longer battery lifetime per pack generates a lower environmental load per driven km.

2.2.2 Repurposing

Repurposing, or second-life, aims to utilise the battery for a different application compared to its initial application. Repurposing is an option when a battery no longer has the SOH required for its 1st life application, and repair is unavailable. For repurposing of batteries from vehicle applications, common proxy is at least 80% SOH remaining as well as a maximum resting self-discharge rate of 5% over 24 hours (Engel et al., 2019; Kalhammer et al., 2007). Repurposing is a beneficial option since it only requires limited resources before it can be used for a new application. This is true if the battery pack is not dismantled in order to reuse individual components such as the module in applications where new material or parts are required.

A relatively new and upcoming repurposing application for BEV batteries is to use them in a grid energy storage system. Grid storage is to balance the peaks of power supply and demand across a power grid. Traditionally, fossil fuel sourced generators have constituted back-up in case of a demand over-load on the grid whereas peak power supply comes with losses due to lack of storage. The results of grid storage are among others increased power grid management and flexibility by providing energy buffering capacity. More than 50% reduction in CO_2 emissions would be possible if an EV battery is repurposed to store off-peak clean electricity to serve peak energy demand (Ahmadi et al., 2014).

Other potential repurposing life applications for BEVs are local storage for solar or wind power, household EV charging or as backup storage (Olsson et al., 2018). As the number of spent BEVs increase, so will the potential for repurposing applications. When a repurposed battery no longer has the health to be used for second-life applications, it will be sent to recycling to regain the valuable materials (Pagliaro & Meneguzzo, 2019).

2.2.3 Recycling

When a battery can no longer be repaired or repurposed it needs to be recycled in order to keep the materials within the system. Recycling might be necessary when the SOH of the battery is too low for repurposing or when the battery is damaged to a degree where it is deemed unusable or unsafe. It is important to recycle the battery in order to "close the loop" according to a circular business model. The cost of the cathode material (e.g. lithium, nickel, cobalt and manganese) and anode material (e.g. graphite) are highly valuable and makes up about 50-60% of the cost of a module (Wentker et al., 2019). The monetary value of recycling depends on market, where in some markets automotive manufacturers get paid to recycle batteries and in others, they must pay for the service of recycling. The EU directive 2006/66 states that *"producers (in the Member States) should finance the costs of collecting, treating and recycling all collected batteries and accumulators minus the profit made by selling the materials recovered"* (European Parliament, 2006).

There are three possible routes for recycling lithium-ion batteries, pyrometallurgical process, hydrometallurgical process and direct recycling. The latter is currently not used at industrial scale. Pyrometallurgy uses high temperature smelting techniques. The first step is a mechanical pre-treatment followed by a heat treatment where the different materials are separated (Assefi et al., 2020). Hydrometallurgy is a chemical process where the material is leached in acids where the first step is to shred the components and then magnetically separate them to extract what is referred to as "black mass". This is followed by sieving and water density separation where after black mass is leached to separate the materials from each other (lithium, nickel, cobalt, manganese & graphite) (Vieceli et al., 2018). Studies have shown that with new technologies, it's possible to recover up to 99% of lithium from a recycled battery pack (Chen et al., 2015).

2.3 Climate impact assessment

To quantify the CO_2 emissions from the different components in the battery pack, data from various sources has been used, namely Volvo Cars, literature and Ecoinvent. The latter is a database which provides datasets for modelling background processes for a wide variety of technologies and processes. The methodology of life cycle assessment (LCA) is described below together with a more in-depth description of the emission quantification including the terms carbon footprint and carbon dioxide equivalents (CO_2e) which are used extensively throughout this thesis.

2.3.1 Life Cycle Assessment

LCA is an environmental analysis technique used to assess the environmental impact of a product or service over its lifetime (European Environment Agency, 2022). LCA includes four main steps:

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

(Hauschild, 2017). This structure follows the ISO 14040 standard (International Organization for Standardization, 2006).

In the goal and scope definition, the goal of the study is defined including the research questions to be answered and who the audience of the study is. In addition to this, a functional unit is defined, which is a quantitative description of the function or service for which the assessment is performed. It is normalized in order to be expressed as a reference flow in the study (Hauschild, 2017). During the inventory analysis, information about the physical flows such as input of resources, materials, products and the output of emissions, waste and valuable products for the product system is collected. The compiled inventory results are then used in the impact assessment where the environmental impact of the different stages are assessed and quantified for different impact categories (Hauschild, 2017). The results from the impact assessment are then to be interpreted during the last phase. This includes a sensitivity analysis where the robustness of the results is tested. All stages are repeatedly subject to interpretation. There are several benefits of using LCAs, for example it allows for a systematic assessment, comparability and quantification of emissions and footprints (Muralikrishna & Manickam, 2017). Life cycle cost (LCC) is a term that is commonly used in conjunction with LCA as an economic analysis commonly accompanies an environmental analysis. LCC can be defined as the sum of the costs throughout the entire life cycle of a product. It can assist decision makers in choosing the best investment plan (S. Yang et al., 2020).

2.3.2 Emission quantification and metrics

To determine the environmental impact of the battery repair and the related processes, quantification of the environmental impact is crucial. An LCA quantifies certain GHG emissions during a the lifetime of a product. These will be used to allocate emissions for different steps in the process. Emission metrics provide, in a similar way as exchange rates for monetary currencies, to measure the contributions of different GHGs to climate change. A commonly used metric is the Global Warming Potential (GWP). It is defined as the accumulated radiative forcing[2] within a specific time horizon, commonly 100 years, caused by emitting one kilogram of the gas, relative to that of the reference gas CO_2. This metric is used to transform the effects of different GHG emissions to a common scale, CO_2e and is defined as:

'The amount of carbon dioxide (CO_2) emission that would cause the same integrated radiative forcing, over a given time horizon, as an emitted amount of a GHG or a mixture of GHGs.'

(IPCC et al., 2014)

In this thesis, the environmental impact is measured by the carbon footprint i.e. through the quantities of CO_2 emitted, specifically kg CO_2e for a certain product or process. The carbon footprint is defined as:

'Sum of GHG emissions and GHG removals in a product system, expressed as CO_2-equivalents and based on a life cycle assessment using the single impact category of climate change'

(International Organization for Standardization [ISO], 2018)

[2] The change in the net radiative flux at the tropopause or top of atmosphere due to e.g. change in the concentration of CO_2 or the output of the sun (Enting, 2018)

3 Methods

This chapter describes the method of the thesis. First, an introduction to the methods of information research such as the literature review and process mapping is given. This is followed by specifications on how data on CO_2 emissions, costs and transport, was collected. Lastly, the chapter is concluded with a description of how a climate impact and cost analysis was done, resulting in a decision support tool.

3.1 Literature and information review

Initially, a literature review was conducted to gain understanding about the field of EVs as well as key topics and the terminology used in the field. The focus of this literature review was battery electric vehicles in the context of climate impact. The following key words were used to filter out scientific papers: *climate change assessment, carbon dioxide, circular economy, battery electric vehicle, high voltage battery, lithium-ion, climate impact, second-life, repair, life cycle assessment.* The literature review was limited to articles and studies from the past 10 years to ensure reliable data due to the rapid development and research in the field of electric vehicles and high-voltage batteries in the past decade.

An internal review of the documents available at Volvo Cars was also carried out. The purpose of this internal review was to identify the technical aspects of the specific battery pack under investigation and its integration with the Volvo Cars vehicle fleet as well as to gain information about the methodologies used in the repair process.

3.2 Process mapping

In order to gain understanding and providing an overview of the process flow and the decisions influencing the process of dealing with a faulty BEV battery, a process map and a decision tree was created. The starting point represented the process step where a battery pack issue was being identified and the end point represented the process step at which the solution to the issue was implemented.

The process map was created based on 1) observations in the battery center, 2) discussions with technicians on site and 3) repair method protocols. The process map covers the chain of steps a battery undergoes from the identification of a battery pack issue, through the processes in the battery center at Volvo Cars, until an endpoint is reached. The decision tree was created by identifying the decisions being made throughout the process chain. This included semi-structured interviews with staff at the department of Battery Lifecycle Services as well as technicians in the battery center. A sample of key persons were selected and interviewed using open questions. These questions were used to gain an initial understanding of the process. With the data and information collected, the flowchart and decision tree was created using Microsoft Visio. To ensure a high level of accuracy in the findings, the flowchart was cross-checked against existing repair method protocols.

3.3 Climate impact and cost analysis

In this thesis, a climate impact analysis and cost analysis were conducted respectively and the procedures for the two are described below.

3.3.1 Climate impact analysis

To account for the environmental impact of repairing a battery pack, both manufacturing as well as transport emissions were accounted for. The pack manufacturing emissions included those from the manufacturing of the initial battery as well as those from the manufacturing of new spare parts needed for repair. For the modules, the results from a cradle-to-gate LCA from Volvo Cars on the vehicle, into which the battery under study is integrated, were used. For the other non-module components in the pack, component-specific CO_2 data was collected from literature or databases. A conceptual model was created to manage the complexity of the many components included in the pack. An overview of the conceptual model can be seen in figure 3.1.

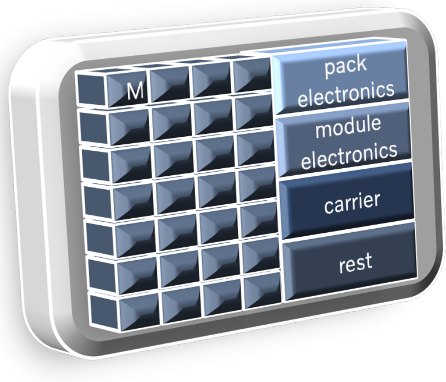

Figure 3.1: The conceptual model showing the battery pack and its parts, with the cell modules indicated with 'M' to the left and the other main components to the right

The conceptual model states that the battery pack consists of some main parts: cell modules, pack electronics, module electronics, a carrier and a 'rest'. This approach was chosen based on data availability, repair frequency and possibility of repair in the battery center. The pack electronics and module electronics are two separate electronic components connected to the modules and the pack respectively, the carrier is the supporting aluminium tray that the battery is placed on. The 'rest' is an aggregation of the remaining components of the pack which are assumed to be fixed and non-repairable and its value will only be used to assign emissions to a complete pack. The investigation and quantification of all the components included in 'rest' falls outside the scope of the thesis.

Scenarios were created enabling the comparison of environmental impact for different repair scenarios in relation to changing the entire pack. The following assumptions were made to enable those scenarios:

- The lifetime of a new BEV battery pack in a vehicle is 200 000 km
- When a battery pack exchange is conducted, the old pack is considered spent
- When a module and/or any component in the pack is repaired, the lifetime of the battery pack is **not** prolonged, instead the repair enables the continuation of the full lifetime of the pack

3.3.2 Cost analysis

To quantify the cost of repairing a battery pack or its components, different factors were accounted for. First, the purchasing cost, or the actual cost of purchasing the component replacing the broken or degraded component needs to be determined. Secondly, the transport costs, or the cost of shipping the spare parts need to be added. Furthermore, the labour cost was added to give the full cost picture. Since reliable and comprehensive cost data existed, modelling of the costs was not needed. The costs were calculated as described below in 3.5.4.

Because the cost data used in this thesis is confidential under non-disclosure agreements, a new fictional currency was made up and used in this thesis. The relative sizes of the costs are accurate but the actual costs are modified. The currency used is Volvo Cars Dollar (VCD).

3.3.3 Identification of repairable components

During the use phase of a BEV battery pack lifetime, certain parts break more frequently than others and are therefore also more frequently repaired. These components were identified using failure frequency data from the battery center at Volvo Cars but also from dealer workshops in markets throughout EMEA. Discussions with technicians in the battery center were conducted in order to determine which components were possible to repair and which were not. Based on this, components were included in this study based on two conditions:

- High failure frequency
- Component is repairable at the Volvo Cars battery center in Gothenburg

The data included a total of 488 repairs, including repairs that had previously been done at dealer workshops. In the foreseeable future, the vast majority of all repairs for BEV batteries will be done at Volvo Cars' battery centers, in comparison to the past when dealers have conducted certain repairs. The data spanned over a period of one year (2021). Because of the increasing number of BEV packs entering the market, the number of repairs will increase. This can have an impact on which of the components that are most likely to fail within a pack and needing repair. However, this uncertainty is considered to have a limited effect on this study and the key components were verified by experts within Volvo Cars.

3.4 Repair scenarios

Using the repair data described above, the scenarios 'common', 'min' and 'max' were identified for a battery that was to be repaired in the battery center. The baseline scenario was used for the comparison with the other scenarios.

Baseline: The whole battery pack is exchanged for a new one at a dealer workshop

Scenario "Common": Changing two modules, one pack electronic unit, two module electronic units and where battery pack breakdown occurs in the Netherlands

Scenario "Min": Component with minimum CO_2 emission is repaired, battery at a minimum distance from the battery center

Scenario "Max": Everything is repaired, battery at the furthest distance from the battery center

The common scenario was chosen as it represents what can be seen as a frequent repair scenario in the battery center. The min and max scenario were chosen to show the extreme points of repair. In addition to be used as a basis for comparison, the scenarios will also be used in the sensitivity analysis to highlight the impact a change in one of the parameters can have. The scenarios were identified with repair frequency data and through discussions with employees at Volvo Cars and at the battery center.

3.5 Data collection

The data used in this thesis was collected from various sources. Internal Volvo Cars data was gathered via internal documentation as well as through discussions with experts and Volvo Cars employees.

Often, initial discussions were needed to identify what data was available before extraction was possible. The repair of BEV battery packs, being a relatively new practice given their short presence on the market, was not extensively documented at this point why discussions with technical experts and employees was crucial. The information was evaluated, and the relevant data was selected and further processed. In figure 3.1 below, the main parameters of interest in this thesis are introduced.

Table 3.1: Main parameters of interest with description and assigned units

Parameter	**Description**	**Unit**
$C_{components}$	Purchasing cost for one component	VCD
$C_{technician}$	Labour cost for one technician	VCD/hour
$C_{transport}$	Cost of transporting batteries and spare parts	VCD
$d_{transport}$	Transport distance for batteries and spare parts	km
$E_{components}$	Emissions from components	kg CO_2e
$E_{transport}$	Emissions from transport	g CO_2e/tkm
$m_{components}$	Weight per component	kg
t_{repair}	Time it takes to repair one component	hours
$v_{components}$	Volume per component	m^3

3.5.1 Emission data

The emission data for the modules were provided by the Sustainability Center at Volvo Cars. For the non-module components, a study performed by Ellingsen in 2014 on a 26,6 kWh Li-ion NMC111 battery was used along with data from Ecoinvent. The non-module data used from Ellingsen's study for the remaining components is judged valid and is assumed to not have changed much since it was published. Thanks to the high transparency and detail of Ellingsen's study, the results could be scaled and extrapolated to fit the specific battery under investigation in this thesis.

The allocation to the specific components was done by using background data from Ellingsen's study and from Ecoinvent. More specifically, for the module electronics, the pack electronics and the rest, data from Ellingsen's study was used whereas for the carrier, data from Ecoinvent was used.

The data from Ellingsen's study was used to assign emissions to the electrical components included in this thesis, whose counterpart in Ellingsen's study are called IBIS and BMB and can be seen in figure 2.2. Ellingsen's study was also used to allocate the emissions from the complete battery using equation 3.6. To determine the emissions per module, the total emission for all modules are divided by the number of modules as shown in equation 3.1 below.

$$E_{module} = \frac{E_{all\ modules}}{number\ of\ modules} \tag{3.1}$$

To allocate the emissions for the pack electronics, the emission value from Ellingsen's study for the IBIS was used without any modifications in equation 3.2. In Ellingsen's study, there is one unit of IBIS per pack and the same is true for the studied battery pack. It's assumed that the studied 78 kWh battery uses the same pack electronics as Ellingsen's 26,6 kWh battery, i.e., that the type of pack electronics is independent of the battery capacity within these ranges.

$$E_{pack\ electronics} = E_{IBIS} \tag{3.2}$$

For the module electronics, a different approach was used. Here, Ellingsen's study used 1 module electronics unit for each module, i.e., 12 in total, whereas in the Volvo Cars battery there is 1 module electronics unit per 3 modules resulting in 9 units for the studied battery. In order to solve this, the total emissions calculated in Ellingsen's study was divided by 12 to get the value per module electronics in the Volvo Cars battery, see equation 3.3 below. It's assumed that the studied 78 kWh battery uses the same module electronics as Ellingsen's 26,6 kWh battery, i.e., that the type of module electronics is independent of the battery capacity within these ranges.

$$E_{module\ electronics} = \frac{E_{BMB}}{12} \tag{3.3}$$

For the carrier, Ellingsen's study modeled the carrier using steel unlike Volvo Cars who uses aluminium. This means that the data used in Ellingsen's study was not directly applicable in the Volvo Cars case. To solve this, data from Ecoinvent v3.8 and weight data from Volvo Cars were used to determine the emissions for the aluminium carrier. The emissions allocated to the aluminium carrier were due to three different production processes: production of primary aluminium, extrusion and milling. The emissions from the aluminium carrier were calculated according to equation 3.4 below.

$$E_{carrier} = (E_{Al,production} + E_{Al,extrusion} + E_{Al,milling}) \cdot m_{carrier} \tag{3.4}$$

The aggregated remaining parts of the pack, i.e., the rest, are classified as non-repairable have been allocated emissions using the data from Ellingsen's study and then scaled based on the weight of the components in the Volvo Cars pack. The total emissions for the remaining components in Ellingsen's battery were divided by the total weight of these components. This gave a CO_2 load per kg of rest. The emissions from rest were then calculated as per equation 3.5 below.

$$E_{rest} = \frac{E_{rest,Ellingsen}}{m_{rest,Ellingsen}} \cdot m_{rest,Volvo\ Cars} \tag{3.5}$$

The sum of CO_2 emissions from the components are dependent on the number of components that are exchanged during the repair and were calculated according to equation 3.6 below.

$$\sum CO_{2,\ battery\ pack} = E_{modules} \cdot m + E_{pack\ electronics} \cdot b + E_{module\ electronics} \cdot i + E_{carrier} \cdot c + E_{rest} \tag{3.6}$$

where

m = number of modules repaired [0-27]

b = number of pack electronic units repaired [0,1]

i = number of module electronic units repaired [0-9]

c = number of carriers repaired [0,1]

The numbers within brackets shows how many of the different components that can be repaired in one pack, e.g. between 0 and 27 modules can be repaired. There is no factor for E_{rest} since it's assumed to be non-repairable. E_{rest} is only included to in the total emissions for a new complete battery pack.

3.5.2 Transport data

For transports, internal data from Volvo Cars was used to the highest extent.

Volvo Cars uses a network of local distribution centers (LDCs) in Europe to coordinate shipments to and from the dealer workshops within each country. From these LDCs, the BEV batteries were transported back to the central distribution center (CDC) in Gothenburg. In order to allocate emissions from the transport of the different components, a few countries of interest were selected based on the frequency of repairs for different EMEA market countries in 2021. The six countries with the highest repair frequency were selected where after all the LDCs within each of the countries were mapped. A distance to the country was calculated using the average distance from the CDC to each of the LDCs.

A road LTL (less-than-truckload) truck loaded with on average 8 tons of cargo was assumed for all transports. This is the most common truck used by Volvo Cars within the European market for transporting spare parts. The truck currently transports spare parts together with BEV batteries. To allocate emissions for the transport of the batteries an average emission factor given in CO_2e/tkm (tonne kilometer) provided by Volvo Cars was used. This factor was multiplied by the distance travelled and the weight of the battery pack, excluding packaging. The distance for $d_{CDC-LDC}$, i.e., to and from the markets, were assumed to be the same. The emissions arising from the distance CDC to the battery center was assumed to be negligible. Furthermore, the distance from the workshop to the LDC i.e., the last mile distance was assumed to be 200 km for all countries and was assumed to use the same type of truck as between CDC-LDC. The emissions arising from transporting a used battery pack from a workshop to the battery center, return trip were calculated with equation 3.7.

$$E_{transport,used\ pack} = 2 \cdot (EF_{truck,EMEA} \cdot m_{component(s)} \cdot (d_{LDC-CDC} + d_{lastmile})) \quad (3.7)$$

When a newly produced battery pack had to be sent out to a dealer workshop, this pack was assumed to be sent from the Volvo Cars factory in Ghent, Belgium. The distance was calculated in the same way as for the distance from the CDC to the LDC's and the truck was assumed to be the same as for the transport from the LDC to the CDC. The emissions arising from transporting a new battery pack from the factory in Ghent to the dealer workshop, were calculated with equation 3.8.

$$E_{transport,new\ pack} = EF_{truck,EMEA} \cdot m_{battery\ pack} \cdot (d_{Ghent-LDC} + d_{lastmile}) \quad (3.8)$$

For the transport of spare parts i.e., modules, carrier and the two electronic parts from the supplier to the battery center, emissions were allocated to each of the components. All suppliers are located in China and truck transport was assumed from the supplier to Shanghai (SHG), followed by transport by cargo ship from Shanghai to Gothenburg. The emissions arising from the port of Gothenburg to the battery center was assumed to be negligible. The emissions were calculated using the same method as for the truck i.e., using an emission factor, the weight of the components and the distance travelled. The emissions from the transport of the spare parts are calculated according to equation 3.9.

$$\begin{aligned} E_{transport,spare\ parts} =& (EF_{ship} \cdot m_{component(s)} \cdot d_{SHG-GOT}) \\ &+ (EF_{truck,APAC} \cdot m_{component(s)} \cdot d_{supplier-SHG}) \end{aligned} \quad (3.9)$$

All emissions for the transports, $E_{transport,spare\ parts}$, were determined from internal data on emission factor ($EF_{truck,EMEA}$ & EF_{ship}) and distance (d) travelled according to equation 3.10 below.

$$\sum CO_{2,transport,repair} = E_{transport,used\ pack} + E_{transport,spare\ parts} \quad (3.10)$$

3.5.3 Total emissions

The total emissions from the repair was calculated by adding the emissions from the components and the transports in equation 3.11.

$$\sum CO_{2,repair} = \sum CO_{2,\ battery\ pack} + \sum CO_{2,transport,repair} \quad (3.11)$$

Note that in this sum, the emissions associated with the labour is not included as it is not quantified in this study. The cost of labour is however included in the total cost of the repair as can be seen in equation 3.14.

To calculate the emissions when a pack was exchanged for a new, equation 3.12 was used.

$$\sum CO_{2,new\ battery} = \sum CO_{2,\ battery\ pack} + CO_{2,transport,new\ battery} \tag{3.12}$$

Equation 3.11 shows the total CO_2 load from the activities involved in repairing a battery. This included the transport of the battery from the LDC somewhere in Europe to the CDC in Gothenburg and the transport back to the LDC. The calculated CO_2 load was compared to the load of producing a new battery as shown in equation 3.12. Observe that E_{rest} is equal to zero in equation 3.11 since it cannot be repaired but is included in equation 3.12 as it's contributing to the total emissions of a pack.

In order to have a relative measure of the CO_2 impact of a specific repair, equation 3.13 was created.

$$CO_{2\ per\ km} = \frac{\sum CO_{2,battery\ pack}}{d_{lifetime}} + \frac{\sum CO_{2,repair}}{d_{lifetime} - d_{mileage}} \tag{3.13}$$

For the left term of the equation, the emissions from the manufacturing of a new pack were divided over a pack's full lifetime of 200 000 km. This gives a relative value for how much the manufacturing of the battery pack contributes to the total emissions, given that the battery lives 200 000 km. As this term is independent of repair scenario, it is considered a constant in this equation. For the right term of the equation, the emissions for an arbitrary repair scenario are divided by the remaining lifetime km after the repair is conducted. The reason is that the utility from a repair only contributes to the remaining lifetime distance following the repair. Therefore, the emissions that the repair generates are divided over that same distance i.e., $d_{lifetime}$ - $d_{mileage}$. This gives a relative value for how much a certain repair of the battery pack adds to the total emissions over the distance the repair enables. This part of the equation is dependent on the mileage at repair is such a way that the CO_2 impact from the repair will increase the higher the mileage at repair.

The equation is not meant to provide an optimal mileage to repair in order to ensure low emissions, but rather to relate the CO_2 impacts both from manufacturing and repair to the lifetime of the vehicle. According to the assumptions, a repair does not prolong the lifetime of the battery pack beyond 200 000 km. This is because additional parts than the ones repaired in the pack are expected to fail within the lifetime which would make the pack non-functional.

3.5.4 Cost data

To facilitate and include the financial aspect of the repair system, cost for repairing a battery was needed. This included both the material, i.e., component cost as well as the labour cost. This data was collected internally at Volvo Cars. In addition to this, some of the transport costs have been considered, more specifically the cost of the transport between the workshops and CDC and the transport from the spare part suppliers to the battery center. The cost of transporting a new battery from Ghent is a fixed cost that is dependent on the country that will receive the new battery. This cost was assumed to be the same as the cost to transport a battery from the battery center to a workshop.

To calculate the cost of repairing a component, equation 3.14 was used

$$\sum C_{repair,\ battery} = C_{component} + (C_{technician} \cdot t_{component}) \tag{3.14}$$

The component cost was set per component. The total cost for the technician was determined by the labour time multiplied with $t_{component}$, the time each repair requires. This together generates the cost of the repair, excluding the transport cost. In addition to these costs there are labour costs for the testing and logistics before and after the repair, however these are not within the scope of the repair.

To calculate the cost of transportation, equation 3.15 was used.

$$\begin{aligned}\sum C_{repair,\ transport} =& 2 \cdot C_{last\ mile(Nordics/Rest\ of\ EU)} + C_{supplier-SHG} \\ & + C_{SHG-GOT}\end{aligned} \tag{3.15}$$

This is the cost of the transport of one battery pack to be repaired along with the cost of transport for the necessary spare parts to conduct the repair.

In equation 3.15, the cost of transporting spare parts from Shanghai to Gothenburg with ship was calculated. The cost for the shipping was given for a certain volume in a shipping container, why the cost is multiplied with the volume of the component.

$$C_{SHG-GOT} = v_{component} \cdot C_{SHG-GOT} \tag{3.16}$$

In the same way, the cost of the transport for the spare parts from the suppliers to the port in Shanghai was calculated using the volume of the components and a cost factor for the truck.

$$C_{supplier-SHG} = v_{component} \cdot C_{supplier-SHG} \tag{3.17}$$

So, the complete cost of repairing a battery was calculated according to equation 3.18.

$$\sum C_{repair} = \sum C_{repair,\ battery} + \sum C_{repair,\ transport} \tag{3.18}$$

In order to study how the costs from the repair are varying with lifetime of the pack, one can divide the cost over mileage at the time of the repair. This was done by using equation 3.19.

$$C_{per\ km} = \frac{C_{battery\ pack}}{d_{lifetime}} + \frac{\sum C_{repair}}{d_{lifetime} - d_{mileage}} \tag{3.19}$$

3.6 Sensitivity analysis

A sensitivity analysis reporting on last mile distance impacts per km driven was included in order to investigate the influence on total transport CO_2 emissions and therefore environmental load of the last mile. An additional sensitivity analysis with respect to the electricity mix used during aluminium manufacturing was performed in order to assess how the electricity mix used in production influences the total impact on the component emissions. Finally, different emission values for the cell modules were also analyzed to identify any major effects on the total CO_2 impact from the modules and to investigate the robustness of the results.

3.7 Decision support tool

In order to calculate and visualize the different repair scenarios a decision support tool (DST) was created. It was created using Microsoft Excel and enables the user to select which parts that will be repaired and how long the car has been driven at the time of failure. The decision support tool calculates the emission and cost data to evaluate the given scenario and show what the potential saving or loss of the repair is. In addition to this, it also shows what the CO_2 emissions or costs are divided over the driven distance.

4
Data Inventory and Analysis

4.1 Battery Center

The Volvo Cars battery center is located on the premises of the Volvo Cars factory in Gothenburg, Sweden. The Gothenburg battery center serves the EMEA region only. There are currently three workers in the battery center of which two are technicians working with repairing batteries in the battery workshop and one handles the logistics. The battery center only handles batteries from the aftermarket and no new batteries and is currently in an expansive phase as the battery volumes are expected to increase significantly in the coming years as more BEVs enter the market.

4.1.1 Process Mapping

An action is initiated when a BEV with a faulty HV battery arrives to a dealer workshop. The dealer starts with an initial investigation to identify the problem and the location of the fault. Based on this investigation, the battery is color coded according to the system in figure 4.1. This color classification determines what actions are to be taken by the dealer and eventually by Volvo Cars, if the battery needs action at the battery center.

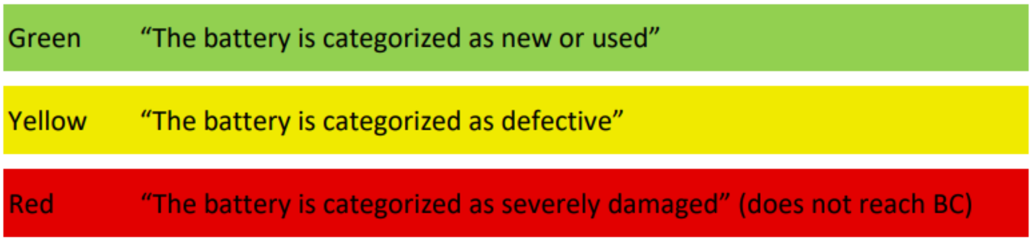

Figure 4.1: Color classification of faulty BEV batteries indicating the status of a specific battery pack.

Figure 4.2 shows the process flow for a faulty BEV battery, which is a simplified version of the actual process.

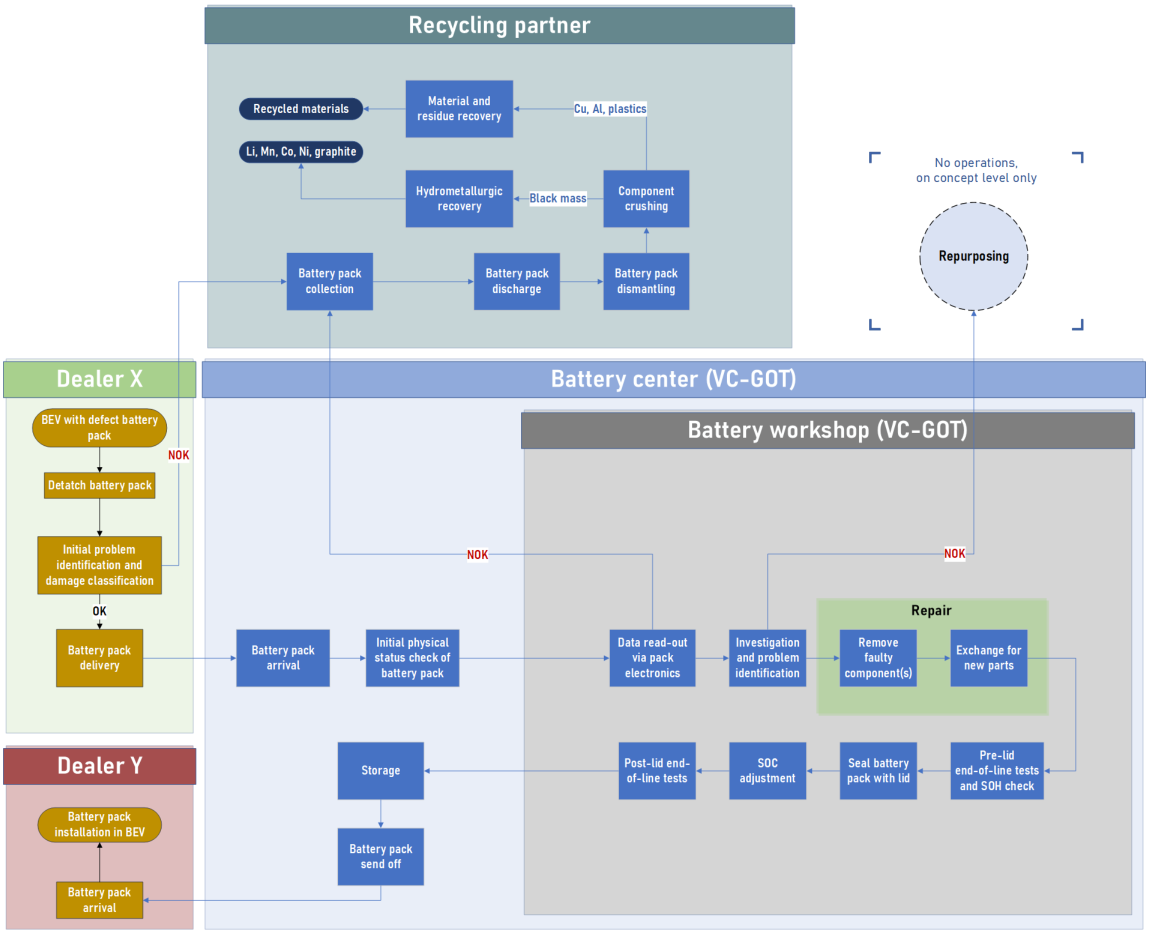

Figure 4.2: Process flow of a faulty BEV battery. Starting at dealer X, through the battery center until its end point i.e. dealer Y, repurposing or recycling.

The process starts when a dealer X, of a Volvo Cars associated workshop somewhere within the EMEA market, receives a BEV with a faulty or damaged battery pack. The dealer performs a problem identification and assigns a color according to the color classification. A red color classification indicates severe damage on the battery pack and the pack will be sent to recycling without prior actions, i.e. not be sent to the battery center. A green or yellow color classification corresponds to that the battery pack will be shipped to the battery center in Gothenburg for further inspection.

Once the pack has been received by the battery center, a physical and visual inspection will be done followed by an error data readout from the pack electronic unit. This is done to confirm or reject the suggested problem indicated by the dealer. Depending on the outcome of this step and on the SOH of the battery, it will be determined suitable for either repurposing, repair or recycling by the technicians in the battery center.

If the battery is determined repairable, the battery will be moved into the workshop and the battery pack lid will be opened and the repair will start. Assisted by the pack electronics' error readout, measurements and tests are performed on the pack in order to find the faulty component(s). When detected, the repair process starts, and the target components are removed and exchanged using a standardized protocol. Following this, the battery goes through several end-of-line tests to verify its functionality and correct adjustments. The battery pack lid is later attached, and the battery is charged to a specific SOC level. Some final end-of-line tests are performed to make sure that the battery operates in the desired way and that the pack is fully sealed. Depending on whether a request of a battery pack exists from a dealer or not, the battery is stored in the battery center for some time or shipped immediately to a dealer (Y).

4.1.2 Decision mapping

The decisions associated with the handling a faulty BEV battery can be observed in figure 4.3 below.

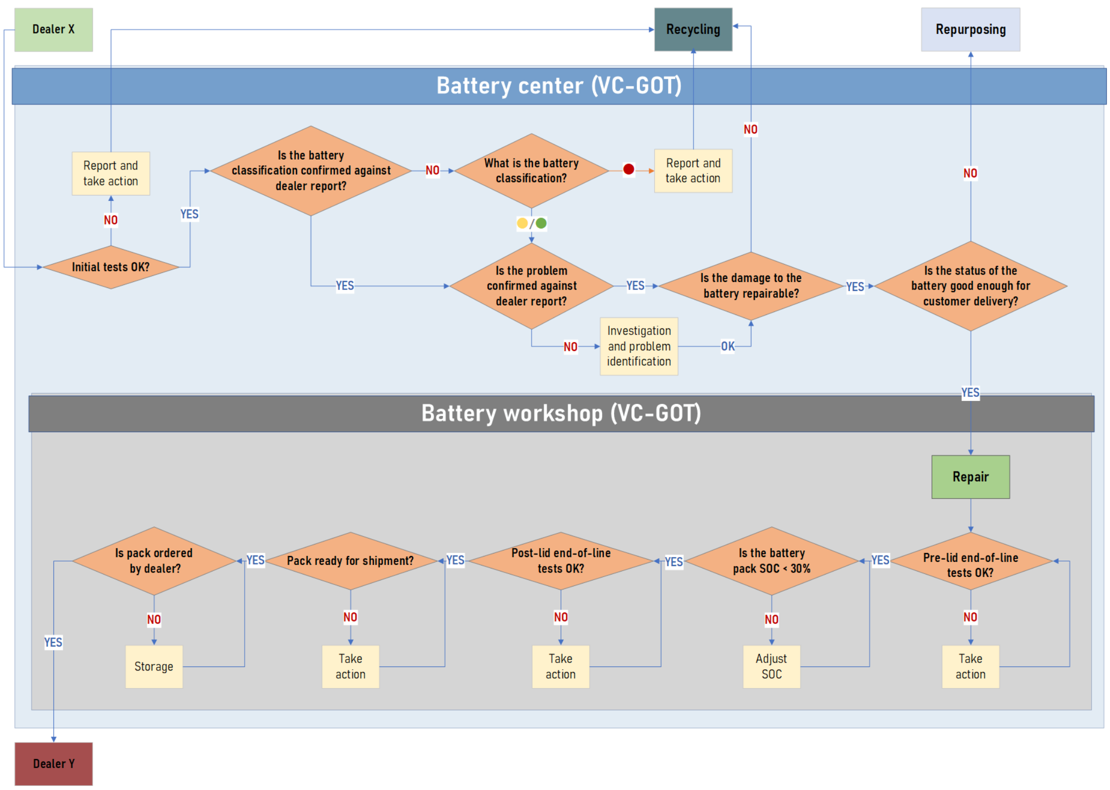

Figure 4.3: An overview of the decisions involved in the BEV battery issue identification process at the battery center.

The diamond shapes represent the questions to be answered by the battery center technicians in order to determine the next step. The yellow boxes are any actions following the answer 'NO' or in one case following the color classification red, indicated by a red circle.

4.2 Data inventory

In this section, all data collected and used to generate results in this thesis will be presented. The data collection has been conducted according to procedures described in chapter 3.

4.2.1 Component data

Table 4.1 displays weight data for individual components in the specific battery pack under investigation. For the battery pack and all components, internal Volvo Cars data was used.

Table 4.1: Weight data of the components of interest, used in equations 3.4, 3.5, 3.7 and 3.9.

Parameter	Value	Unit	Source
$m_{battery\ pack}$	500	kg	Volvo Cars, 2022a
$m_{carrier}$	72	kg	Volvo Cars, 2022a
m_{module}	348	kg	Volvo Cars, 2022a
$m_{module\ electronics}$	0,4	kg	Volvo Cars, 2022a
$m_{pack\ electronics}$	0,6	kg	Volvo Cars, 2022a
m_{rest}	79	kg	Volvo Cars, 2022a
v_{module}	10	dm^3	Volvo Cars, 2022a
$v_{module\ electronics}$	0,1	dm^3	Volvo Cars, 2022a
$v_{pack\ electronics}$	0,7	dm^3	Volvo Cars, 2022a
$v_{carrier}$	27	dm^3	Volvo Cars, 2022a

4.2.2 Emission data

Table 4.2 shows the input data for emissions assigned to the components of interest.

Table 4.2: Emission data for components of interest, used to allocate emissions in equations 3.1, 3.2, 3.3 and 3.5.

Component(s)	Value	Unit	Source
BMB	48	kg CO_2e	Ellingsen et al., 2014
IBIS	67	kg CO_2e	Ellingsen et al., 2014
Modules	7000	kg CO_2e	Volvo Cars, 2020
Rest	292	kg CO_2e	Ellingsen et al., 2014

Table 4.3 shows the emission factors that are used to calculate the emissions for the specific components and the transports associated with them.

Table 4.3: Emission factors for material production and transport, used in equations 3.4, 3.7, 3.8 and 3.9.

Parameter	**Value**	**Unit**	**Source**
Aluminium extrusion	0,98	kg CO_2e/kg Al	Ecoinvent 3.8[a]
Aluminium milling	13,4	kg CO_2e/kg Al	Ecoinvent 3.8[a]
Primary aluminium	23,6	kg CO_2e/kg Al	Ecoinvent 3.8[a]
EF_{ship}	12,0	g CO_2e/tkm	Volvo Cars, 2022b
$\mathrm{EF}_{truck,APAC}$	73,0	g CO_2e/tkm	Volvo Cars, 2022b
$\mathrm{EF}_{truck,EMEA}$	68,0	g CO_2e/tkm	Volvo Cars, 2022b

[a] See table 6.1 in appendix C for the complete data set

4.2.3 Transport data

The following six countries, in no particular order, have been identified as the countries with the highest number of repairs of BEV batteries within the EMEA markets:

- Sweden
- Norway
- Germany
- The Netherlands
- Belgium
- Italy

Within each country there are between 1 to 9 LDCs. The location of each of these can be seen in figure A.1 in appendix A. The transport distance was calculated by determining the average distance from each LDC within one country to the CDC in Gothenburg.

In table 4.4, the distances from each country's LDC to the CDC are presented. The last mile distance, being the distance from the LDC to a specific dealer workshop is assumed to always be 200 km independent of country.

These are the average distances to the LDCs in the respective countries. The values are used to allocated emissions from the transport and will be multiplied by the emission factor (EF) and the weight ($m_{component}$) of the component.

In addition to the transports of the battery packs back to the battery center from the markets faults were identified, transportation of all spare parts from suppliers to the battery center is needed. All suppliers for the components under investigation are located in China. The locations of the suppliers can be seen in figure B.1 in appendix B.

Table 4.4: Average distances from CDC to LDC in the six countries of interest along with the last mile distance, used in equations 3.7 and 3.8.

Parameter	Value	Unit	Source
$d_{Sweden-CDC}$	240	km	Volvo Cars, 2022e
$d_{Norway-CDC}$	300	km	Volvo Cars, 2022e
$d_{Germany-CDC}$	1 000	km	Volvo Cars, 2022e
$d_{Netherlands-CDC}$	1 030	km	Volvo Cars, 2022e
$d_{Belgium-CDC}$	1 210	km	Volvo Cars, 2022e
$d_{Italy-CDC}$	1 780	km	Volvo Cars, 2022e
$d_{last\ mile}$	200	km	Assumption

Table 4.5 shows the transport distances for the spare parts used in the repair. The calculations are based on the data provided by Volvo Cars. The distance from the suppliers to Shanghai are based on a road transport and shows the average distance for the three suppliers located in China. The distance from Shanghai to Gothenburg is based on the average sea freight distance between the two ports.

Table 4.5: Transport distances for spare parts from suppliers in China to Gothenburg, used in equation 3.9.

Parameter	Value	Unit	Source
$d_{SHG-GOT}$	20 000	km	SEARATES, 2022
$d_{supplier-SHG}$	675	km	Volvo Cars, 2022e

The BEV batteries that serve the EMEA market are assembled in the Volvo Cars factory in Ghent, Belgium. The transport distances for the new batteries from Ghent to the LDCs in the six countries respectively can be observed in table 4.6.

Table 4.6: Average transport distances from the factory in Ghent to the respective LDCs in the six countries of interest, used in equation3.8.

Parameter	Value	Unit	Source
$d_{Ghent-Sweden}$	1 310	km	Volvo Cars, 2022e
$d_{Ghent-Norway}$	1 530	km	Volvo Cars, 2022e
$d_{Ghent-Germany}$	560	km	Volvo Cars, 2022e
$d_{Ghent-Netherlands}$	230	km	Volvo Cars, 2022e
$d_{Ghent-Belgium}$	70	km	Volvo Cars, 2022e
$d_{Ghent-Italy}$	1 080	km	Volvo Cars, 2022e

4.2.4 Cost data

Table 4.7 shows the cost data associated with the repair process.

Table 4.7: Cost data for all components of interest as well as for labour, used in equation 3.14.

Parameter	Value	Unit	Source
$C_{battery\ pack}$	267 800	VCD	Volvo Cars, 2022c
$C_{carrier}$	9 730	VCD	Volvo Cars, 2022c
C_{module}	6 330	VCD	Volvo Cars, 2022c
$C_{module\ electronics}$	340	VCD	Volvo Cars, 2022c
$C_{pack\ electronics}$	2 060	VCD	Volvo Cars, 2022c
$C_{technician}$	1 730	VCD/hour	Volvo Cars, 2022c

In table 4.8, the transport costs for all distances of interest are displayed. These are between CDC-LDC, within the Nordics, within the rest of EU, from Shanghai to Gothenburg and from suppliers in China to Shanghai. The transport cost is constant within the Nordics and within the rest of EU respectively.

Table 4.8: Cost data for different transport routes (one-way) of interest, used in equations 3.15, 3.16 & 3.17

Parameter	Value	Unit	Source
$C_{CDC-LDC}$	80	VCD/pack	Volvo Cars, 2022d
$C_{last\ mile\ Nordics}$	330	VCD/pack	Volvo Cars, 2022d
$C_{last\ mile\ rest\ of\ EU}$	500	VCD/pack	Volvo Cars, 2022d
$C_{SHG-GOT}$	1,8	VCD/dm^3	Volvo Cars, 2022d
$C_{supplier-SHG}$	2	VCD/dm^3	Assumed

For the transport between the LDCs and CDC as well as the last mile costs for the last mile delivery in each region, the cost is given per battery pack. The transport costs for the spare parts from the supplier(s) in China to Shanghai and from Shanghai to Gothenburg respectively are calculated using a price per volume for the truck and sea freight transport.

Appendix D shows the estimated working times to repair a specific component which is used to calculate the labour cost for the repair.

4.2.5 Repair scenario data

In table 4.9 the specific repair scenarios are described.

Table 4.9: Specification of repair scenarios, with number of components being repaired along with country of the dealer workshop identifying the issue.

Scenario	Modules	Pack electronics	Module electronics	Carrier	Country
Common	2	1	2	0	The Netherlands
Min	0	0	1	0	Sweden
Max	27	1	9	1	Italy

5

Results

In this section, the resulting CO_2 emissions and costs associated with repairing the specific battery pack under investigation are presented. The calculations to obtain the resulting emissions and costs related to the repair of the battery pack and to the transports will be presented.

5.1 Component emissions

The manufacturing emissions from the separate and aggregated components respectively can be found in table 5.1.

Table 5.1: The CO_2 emissions for the separate and aggregated components of interest, calculated from the data in table 4.2 and equations 3.1, 3.2, 3.3, 3.4 and 3.5.

Parameter	**Value**	**Unit**
$E_{carrier}$	2 735	kg CO_2e/carrier
E_{module}	259	kg CO_2e/module
$E_{module\ electronics}$	4	kg CO_2e/module electronics
$E_{pack\ electronics}$	67	kg CO_2e/pack electronics
E_{rest}	1 210	kg CO_2e

As can be seen in table 5.1, the emissions are given per unit of component. As 'rest' is an aggregation and only exists as a single unit, it has an absolute value. Using this data as input values in equation 3.6 generates the total emissions from the manufacturing of one battery pack.

$$\sum CO_{2,\ battery\ pack} = 11050\ kg\ CO_2e$$

Observe that this number represents the emissions connected exclusively to the manufacturing of the individual or aggregated components of the pack, excluding any other emissions such as transport.

In figure 5.1 below, the total emissions from a newly manufactured BEV battery pack.

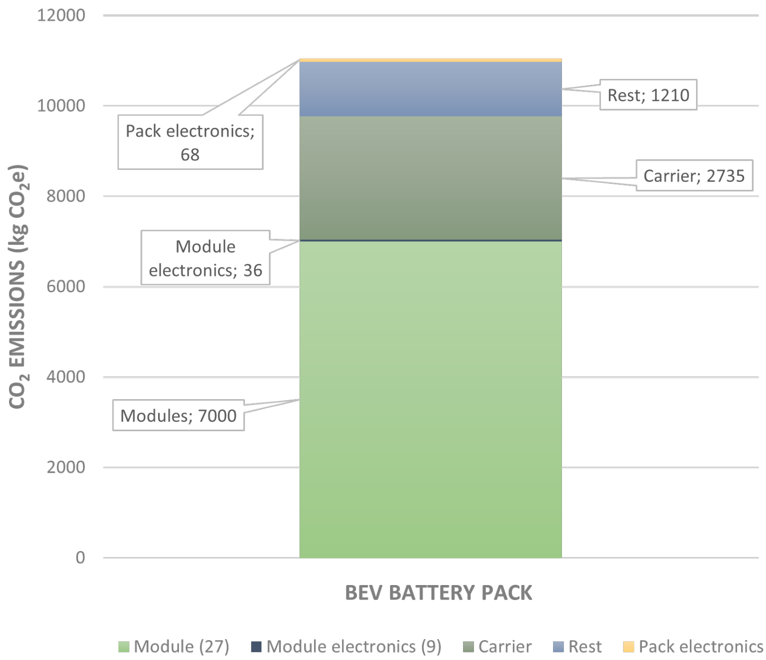

Figure 5.1: The total emissions given in kg CO_2e for a new battery pack with its included components: modules, pack electronics, module electronics, carrier and rest.

As can be seen in figure 5.1, the components responsible for the majority of the emissions are the modules and the carrier. The modules contribution to the emissions increases linearly with each repaired module and range from 0 to 7000 kg CO_2. The aluminium carrier generates the highest emission per unit of component, however that is also the maximal value generated by the carrier as c (the number of carriers repaired) is a binary variable [0,1]. The electrical components, i.e., the pack electronics and module electronics, have relatively low emission values per unit, contributing to less than 1% respectively of the total emissions of the battery pack.

5.2 Transport emissions

Below, the resulting emissions from the transport of an assembled battery pack for two different transport routes can be found. In table 5.2 the emissions generated by the transport truck on the distance between the respective LDCs to the CDC are presented. This table corresponds to the cases where battery packs are sent to and from the battery center. In table 5.3, the resulting emissions generated on the distance from the factory in Ghent, Belgium to the respective countries of interest can be found. These results concern the cases where a brand new battery pack is sent from the Ghent factory directly to the dealer workshop to be installed. Both tables display values where the assumed last mile distance, i.e., distance between LDC and dealer workshop of 200 km, is included.

Using the data from table 4.4 as input values in equation 3.10 generates the emissions found in table 5.2 below.

Table 5.2: CO_2 emissions from the one-way transport of a single faulty BEV battery pack from the respective dealer workshops in the six countries of interest to the CDC.

Country	**Value**	**Unit**
Sweden	15	kg CO_2e
Norway	17	kg CO_2e
Germany	41	kg CO_2e
The Netherlands	42	kg CO_2e
Belgium	48	kg CO_2e
Italy	68	kg CO_2e

Given the set-up of the equation, the emissions generated naturally increase with increased distance from the CDC, with transports within Sweden generating the lowest value of emissions and transports to Italy the highest. Using the data from table 4.6 as input values in equation 3.10 generates the emissions found in table 5.3 below.

Table 5.3: CO_2 emissions from the one-way transport of a newly manufactured BEV battery pack from the factory in Ghent to the respective dealer workshops in the six countries of interest.

Country	**Value**	**Unit**
Sweden	52	kg CO_2e
Norway	59	kg CO_2e
Germany	26	kg CO_2e
The Netherlands	15	kg CO_2e
Belgium	9	kg CO_2e
Italy	44	kg CO_2e

Similarly, the emissions generated naturally increase with increased distance from Ghent, with Belgium generating the lowest value of emissions and Norway the highest.

Looking at the emissions from transporting the spare parts, they vary depending on which and how many components that are being transported. This will be shown more in detail in section 5.3.

5.3 Repair scenario analysis

In this section, the results from the analysis of the different repair scenarios introduced in methods section 3.4, will be presented.

5.3.1 CO_2 emissions per repair

As described in chapter 3.5, using equation 3.6 for a certain repair scenario will output the repair related emissions for that specific scenario.

Common scenario - calculation example
The common scenario, defined as changing 2 modules, 2 module electronic units and 1 pack electronic unit with a battery pack breakdown in the Netherlands, would generate the results below. Spare parts are sent from suppliers in China and shipped from the port of Shanghai.

$$\begin{aligned}\sum CO_{2,\ battery\ pack} =& E_{module} \cdot 2 + E_{pack\ electronics} \cdot 1 + E_{module\ electronics} \cdot 2\\ &= 600\ kg\ CO_2e\end{aligned}$$

$$\begin{aligned}E_{transport,\ used\ pack} &= 2 \cdot (EF_{truck,EMEA} \cdot m_{battery\ pack} \cdot (d_{CDC-Netherlands} + d_{LDC-workshop}) =\\ &= 80\ kg\ CO_2e\end{aligned}$$

$$\begin{aligned}E_{transport,\ spare\ parts} =& (EF_{ship} \cdot (m_{module} \cdot 2 + m_{pack\ electronics} \cdot 1 + m_{module\ electronics} \cdot 2)\cdot\\ & d_{SHG-GOT}) + (EF_{truck,APAC} \cdot (m_{module} \cdot 2 + m_{pack\ electronics} \cdot 1+\\ & m_{module\ electronics} \cdot 2) \cdot d_{supplier-SHG}) =\\ & = 10\ kg\ CO_2e\end{aligned}$$

The total CO_2 load for this scenario is the sum of the emissions from the manufacturing of the spare parts to be changed in the battery pack and the transport emissions, from transporting the pack as well as the spare parts.

$$\begin{aligned}\sum CO_{2,common} =& \sum CO_{2,\ battery\ pack} + E_{transport,\ used\ pack} + E_{transport,\ spare\ parts}\\ &= 690\ kg\ CO_2e\end{aligned}$$

Calculating the min and max scenarios in the same way results in the following emissions, displayed in table 5.4 along with the values for the baseline scenario and the common scenario.

Table 5.4: Total emissions for the three different repair scenarios and the baseline scenario respectively, in kg CO_2e

Scenario	**Value**	**Unit**	**Savings (%)**
Baseline	11 050[a]	kg CO_2e	n/a
Common	690	kg CO_2e	94%
Min	30	kg CO_2e	99%
Max	10 100	kg CO_2e	9%

[a] Excluding transport emission, they are shown in table 5.3

Observe the substantial difference between the min and the max scenario, where the max scenario is over 300 times the size of the min scenario. The max scenario is size-wise comparable to the baseline scenario, where the entire pack is exchanged for a new. The difference between the max and baseline scenario are two, firstly that the baseline also includes 'rest', the non-repairable components, and secondly that max includes the transport emissions.

It is of interest to compare the three repair scenarios to the baseline scenario to determine the quantities of savings of kg CO_2e in the three cases. When comparing the respective scenarios to the baseline scenario, transport emissions have to be added to the baseline scenario, as by default the baseline scenario excludes transport. The baseline scenario, like the other scenarios, is dependent on location of dealer workshop where the new battery must be sent. The quantities of CO_2 savings in the three repair scenarios can be found in table 5.5 below.

Table 5.5: Savings of kg CO_2e per repair in the three repair cases, when comparing to a full exchange of the battery pack.

Scenario	**CO_2 savings**	**Unit**
Common	10 370	kg CO_2e
Min	11 070	kg CO_2e
Max	990	kg CO_2e

Naturally, the largest savings are in the min scenario, when few and low-emission components are repaired. Large emission savings are generated from the common scenario and relatively low from the max scenario.

The influence of transport on the total emissions
In figure 5.2 below, the shares of transport and component related emissions for the the three scenarios are shown. The total emissions for each scenario are displayed in the center of each pie chart.

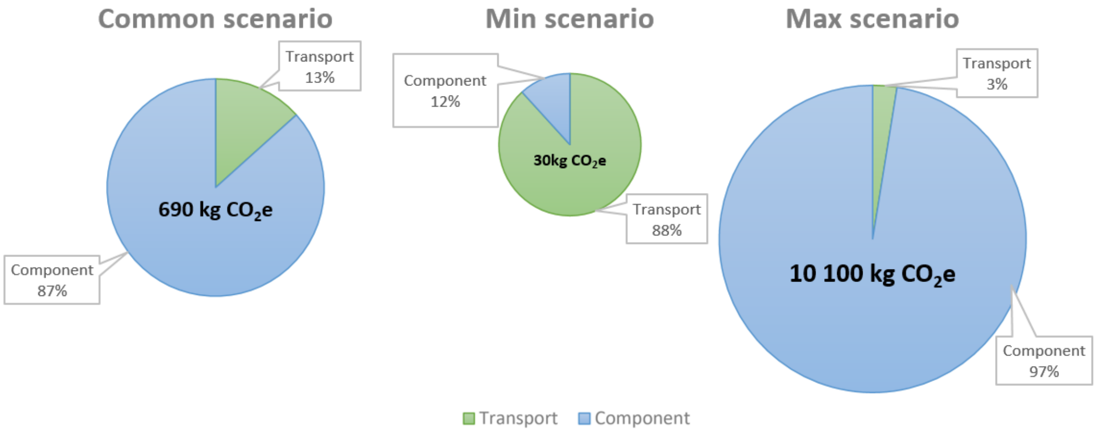

Figure 5.2: The shares of transport and component related emissions respectively of the total emissions for the common, min and max scenario, with the total costs displayed in the centre. Note that the sizes are indicative.

In the max scenario, the transports make up a small share, 3% of the total emissions, whereas in the min scenario, the transports make up most of the total emissions, 88%. Note however, the difference in absolute values between the min and max scenario, 10 100 kg CO_2 and 30 kg CO_2. In the common scenario, the transports make up about 13% of the total emissions.

The influence of the fill rate on the last mile distance emissions
If a battery pack is assumed to account for the entire last mile transport i.e., using a truck for a single BEV battery pack, it generates higher emissions per pack than if multiple packs are transported together. This because the truck will have a certain amount of emissions regardless of if it transports goods or not. The additional emissions comes when the weight of the cargo is increased. This means that when you transport one battery alone, it will in addition to being allocated the emissions from its weight, also be allocated the base emissions for the truck. If multiple packs are transported together, the base emissions for the truck can be split over more packs, thereby giving a lower emission per pack. So, although absolute emissions are higher due to more packs being transported, in terms of emission per pack, it is always environmentally beneficial to transport multiple packs together as they share the load.

5.3.2 CO_2 emissions per lifetime km

In figure 5.3, the CO_2 emissions per lifetime km are plotted against the mileage at repair.

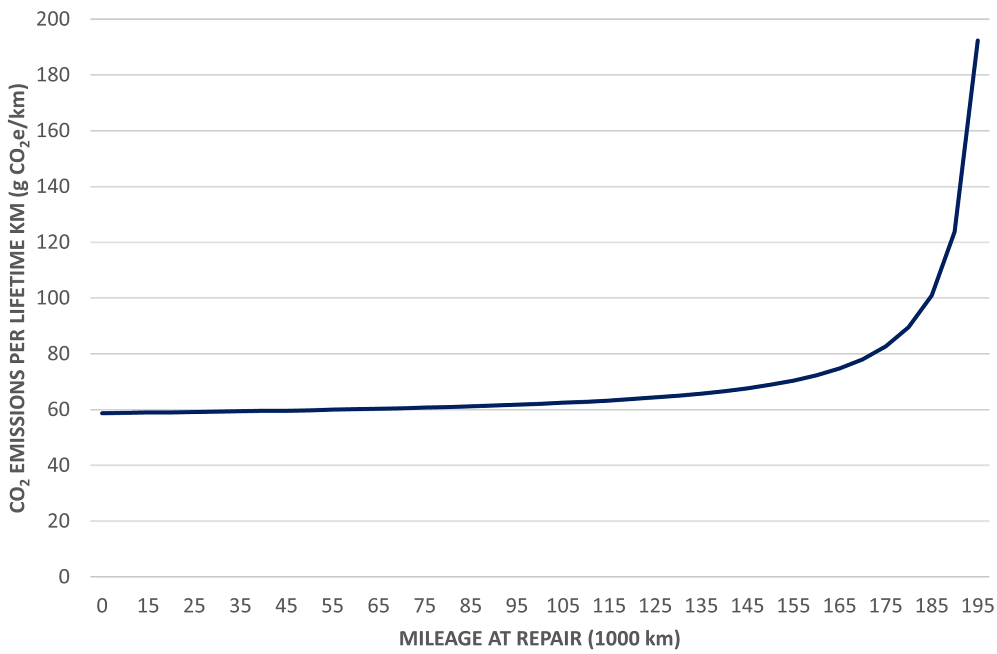

Figure 5.3: The CO_2 emissions per km over the battery pack's lifetime, with the addition of the repair, vs the mileage at repair for the common scenario.

The form of this graph is due to equation 3.13's structure according to the mathematical expression

$$y = \frac{1}{-x}$$

Figure 5.3 shows that the CO_2 emissions per km increase with increased mileage at repair. During the last 30 000 km, the increase rate is the highest, whereas the first 170 000 km the rate is relatively constant.

Common scenario - calculation example
Looking at the emissions from the repair according to the common scenario in relation to a randomly chosen mileage at repair of 100 000 km, the following results are obtained when using equation 3.13.

$$CO_{2\ per\ km} = \frac{11\,050\ kg\ CO_2e}{200\,000\ km} + \frac{690\ kg\ CO_2e}{(200\,000 - 100\,000)\ km} = 62\ g\ CO_2e/km$$

The leftmost term is independent of repair scenario, it is constant and always equal to about 55 g CO_2e per km, given a lifetime of 200 000 km. The addition of the repair, however, will depend on the mileage at repair because the emissions for the specific repair scenario is divided by the remaining lifetime distance after the repair is conducted. At a mileage of 100 000 km, i.e., when also 100 000 km remain for the lifetime, the addition is about 7 g CO_2e per km i.e. the manufacturing emissions from the pack is clearly dominating. This gives a relative value for how much a certain repair of the battery pack adds to the total emissions over the distance the repair enables. The higher the mileage at repair, the less the remaining distance that the repair can be utilized for which results in higher CO_2 impact of the repair and finally, higher emissions per lifetime km.

It's important to note that the action of repair always generate *additional* CO_2 emissions, however, those emissions are in every repair scenario lower than the emissions associated with, the alternative - a full pack exchange.

5.3.3 Costs per repair

Using equation 3.14 for the different scenarios will output the costs associated with the repair according to the specific scenario.

Common scenario - calculation example
Given the common scenario, the following costs will arise from purchasing the spare parts and the repair itself

$$\begin{aligned}\sum C_{repair,\ battery} =& C_{module} \cdot 2 + C_{pack\ electronics} \cdot 1 + C_{module\ electronics} \cdot 2 \\ &+ ((t_{module} \cdot 2 + t_{pack\ electronics} \cdot 1 + t_{module\ electronics} \cdot 2) \\ &\cdot C_{technician}) = 16\ 800\ VCD\end{aligned}$$

The costs of transporting the battery and the spare parts according to the common scenario are calculated using equation 3.15

$$\begin{aligned}\sum C_{repair,\ transport} =& 2 \cdot (C_{last\ mile\ rest\ of\ EU}) + C_{SHG-GOT} + C_{supplier-SHG} \\ &= 1\ 200\ VCD\end{aligned}$$

Equation 3.14 is used to calculate the total cost for the common scenario and the following results are obtained

$$\sum C_{repair} = \sum C_{repair,\ battery} + \sum C_{repair,\ transport} = 18\ 000\ VCD$$

Calculating the min and max scenarios in the same way results in the following costs, displayed in table 5.6, along with the resulting values for the baseline scenario and the common scenario. The difference between the max and baseline scenario are the same as for the CO_2 emissions, that the baseline scenario also includes the cost of 'rest', and that max scenario includes the transport emissions.

Table 5.6: Total costs for the different repair scenarios respectively, in VCD.

Scenario	Value	Unit
Baseline	267 800	VCD
Common	18 000	VCD
Min	1 300	VCD
Max	206 400	VCD

The sizes of the costs are comparable between all the scenarios. The max scenario accounts for almost six times the cost of the min scenario. Figure 5.4 shows the division of costs between the transport, component and labour costs depending on the scenario.

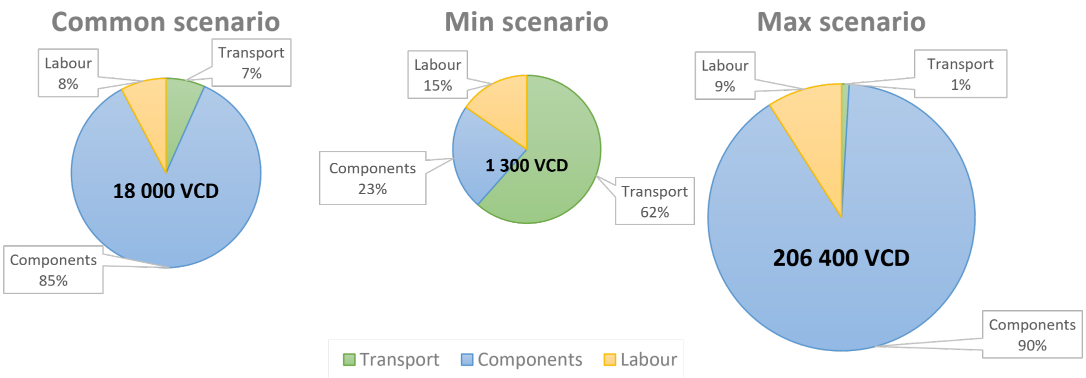

Figure 5.4: Division between transport, component and labour costs for the respective repair scenarios with the total costs displayed in the centre. Note that the sizes are indicative.

A summary of the cost savings in VCD for all three repair scenarios can be seen in table 5.7.

Table 5.7: Cost savings in the three repair cases, when comparing to a full exchange of the battery pack, given in VCD.

Scenario	Savings	Unit
Common	250 300	VCD
Min	266 900	VCD
Max	61 900	VCD

The results show that there are large cost savings possible for all repair scenarios. The difference in savings between the scenarios however, are smaller than for the corresponding results for CO_2.

5.3.4 Costs per repair per km

Common scenario - calculation example

Looking at the costs per km for repair in relation to a mileage at the time of repair of 100 000 km, the results are obtained using equation 3.19

$$C_{per\ km} = \frac{267\,800\ VCD}{200\,000\ km} + \frac{18\,000\ VCD}{200\,000 - 100\,000\ km} = 1,52\ VCD/km$$

Because equations 3.13 and 3.19 are based on the same mathematical expression, a similar trend can be seen for cost as for CO_2. The leftmost term is a constant and always equal to 1,3 g CO_2e per km. At a mileage of 100 000 km, the addition of repair is 0,22 g CO_2e i.e., similarly to the emission case, the manufacturing costs from a new pack is dominating the cost per lifetime km. Similarly, the action of repair always generates *additional* costs but they are lower than the costs associated with a full pack exchange.

5.4 Decision support tool

Here, the decision support tool will be presented. Figure 5.5 shows an overview of the input display of the decision support tool.

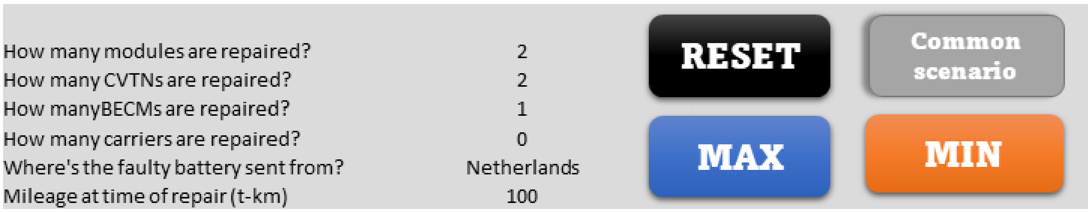

Figure 5.5: Overview of the input display of the decision support tool with values for the common scenario.

On the left side, the components to be repaired are entered including the number of components, the mileage at repair i.e. $d_{mileage}$ and in which country the failure occurred. In figure 5.5 the input data for the common scenario has been entered. On the right side there are four buttons, where *RESET* is used to reset all parameters back to zero, *common scenario*, *MIN* and *MAX* will automatically insert the values for the respective scenario.

In figure 5.6 the output part of the decision support tool can be seen. Potentially negative values imply a loss.

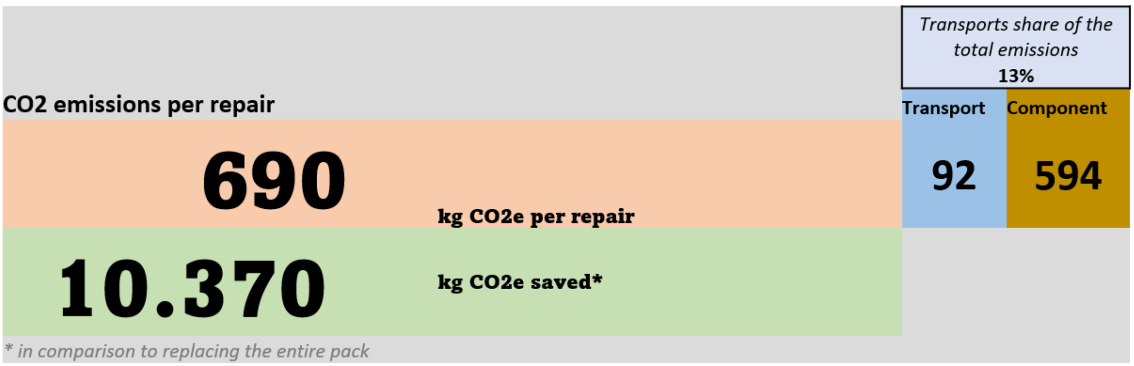

Figure 5.6: Overview of the output display of the decision support tool for the common scenario.

The orange cell shows the total CO_2 emissions for the entered repair case, in this case the common scenario, whereas the green cell shows how the quantity of CO_2 saved or lost compared to a complete pack exchange. The blue and brown cell shows the division of total emissions between the transport and the components of the entered repair scenario. The transport share in percentage of the total emissions can be found in the top right corner.

The input display for the cost modeling has the same layout as the one for the CO_2 modeling shown in figure 5.5. The output display however, has some differences as can be seen in figure 5.7.

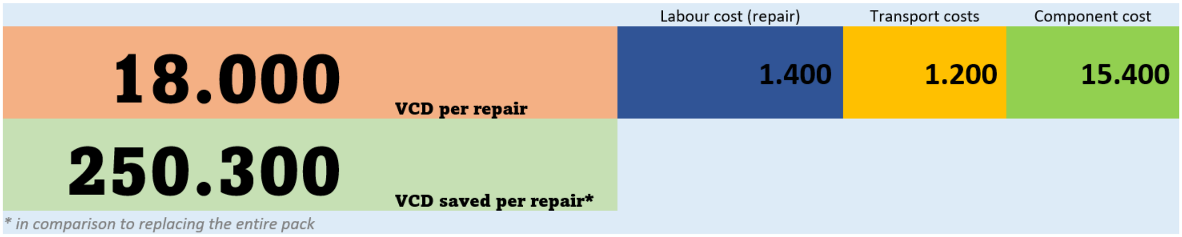

Figure 5.7: Overview of the output display of the decision support tool for the costs for the common scenario.

Here, in addition to showing the cost (orange) and savings (green) per repair, it also shows the repair cost divided into labour cost, transport cost and component cost.

6

Discussion

In this chapter, a discussion regarding the presented results will be conducted for the emissions, transports and costs. In addition to this a sensitivity analysis will be presented.

6.1 Component emissions

The size of the component-related pack emissions, namely 11 050 kg CO_2e, can be compared to driving a Volvo XC40 ICE, emitting about 163 g CO_2e/km[1], roughly 68 000 km (Volvo Cars, 2020). This is equal to a distance almost two laps around the globe, indicating large emissions for a newly manufactured battery pack. To put this in perspective, it's about one third of the expected lifetime of an XC40 (200 000 km).

Looking at the data for the entire battery pack in table 5.1, the modules make up 63% of the total manufacturing emissions. This, in comparison to Ellingsen's study in where the modules make up 75%. A high share generally for modules is reasonable due to that they include the CO_2 emissions from the cell manufacturing, which is commonly driving the environmental impact in BEV batteries. The difference between the fractions in this study and Ellingsen's is likely due to two reasons, 1) that the battery pack in this study is made of aluminium and 2) that Volvo Cars uses virgin aluminium for the carrier. Aluminium production is in itself an energy-intensive process and when an electricity mix with high shares of fossil fuels is used to power the aluminium production, the resulting emissions are high. The carrier alone accounts for 25% of the total pack emissions in this study.

The electrical components have relatively low emission values per unit which indicates that repairing them is generally justified from a CO_2 perspective, even if other components are not repaired. However, electrical components' environmental impact is not extensively mapped through LCAs and some uncertainty in the output values of the electronics is expected. Although, it's assumed that the values used are the most accurate available to date.

The accuracy for the results is highly dependent on the data that has been used. For the modules, primary data from Volvo Cars has been used and for the remaining

[1]tank-to-wheel emissions

components data from Ellingsen's study and the database Ecoinvent has been used. This will have an impact on the end results since there is a variability between different sources in terms of scope and precision, and this could have a large impact on the end results. There will be a difference in emissions depending on with what electricity supply the components are manufactured.

Looking at other circularity alternatives applicable to BEV batteries i.e. repurposing and recycling, some interesting comparisons can be done. While repairing a BEV battery pack, from a CO_2 emissions perspective, results in utilisation of the pack's full lifetime of 200 000 km and lowered emissions per km, recycling puts an end to a battery pack's life. A recycled battery is therefore considered "dead" in terms of lifetime, simply because it's no longer possible to depreciate emissions. However, if the return of materials (e.g., lithium, cobalt, etc.) from the recycling process can be utilized for the recreation of new batteries or other products, it could reduce the need for virgin extraction. This would in turn contribute to an overall lowered carbon footprint of the battery pack. The benefits from the return of materials is dependent on that the battery manufacturer owns or can utilize those benefits, which is currently not always the case.

In terms of repurposing, the battery will have a second life in another application, extending its lifetime. From an emissions perspective, this means that any emissions arising from manufacturing or repair could be depreciated over a longer distance. It will not change the quantity of emissions already emitted, but it will allow a continued storage capacity and a longer lifetime as compared to both recycling and repair. As described in chapter 2.2.2, the possibilities for a second-life application for a pack is dependent on the SOH of that battery pack. With today's knowledge, it's difficult to determine the extended lifetime of a pack in a second-life application and even more so to translate it to expected extended lifetime for a vehicle.

With more EOL knowledge regarding electric vehicles in the future, the carbon footprint from BEV batteries can decrease. More empirical data from the repurposing of BEV packs for grid storage is needed to determine how long they can be utilized and thereby how much of a positive impact that can have from a life cycle perspective. In terms of recycling, the joint venture between Volvo Cars and Northvolt will enable partial or full utilization by Volvo Cars of the benefits from the return of materials.

6.2 Transport emissions

When comparing the transport emissions to the component emissions, it's clear that their sizes differ. Transport emissions vary from around 10-70 kg CO_2e for a one-way transport, staying in the two-digit range. The component emissions, although starting at a lower value per unit, reaches just over 2700 kg CO_2e per carrier and 7000 kg CO_2e for a full module repair. The transport emissions are similar in size to the component emissions for the module electronics and the pack electronics, each making up less than 1% of the total pack emissions. This result indicates that transport is not a driving factor when it comes to the CO_2 emissions from the repair of a BEV battery pack under the circumstances in this study. For example, if all components are changed and the battery is at the maximum distance from the battery center, in this case Italy, the transports will account for 2,5% of the total emissions. This does not mean that the transports are negligible as the fewer components being repaired, the higher the transport share. This low contribution from transports is mainly due to the high emissions from the components and secondly that the BEV battery packs are currently transported together with other goods, lowering the impact per pack.

With time and as the population of BEVs on the market constantly increase, the need for BEV battery repairs will increase and so will the need for battery pack transport. In the future, a possibility is that there will be designated trucks only for BEV pack transport going to and from Volvo Cars' LDCs and CDCs. It is therefore important, now and in the future, to secure that a sustainable truck is used in order to keep the emissions low. During the transport from the CDC to the LDC, Volvo Cars owns the transport and should theoretically be able to choose the most sustainable transport each time. The CDC-LDC route is currently driven on a daily basis. The case for the last mile delivery is somewhat different. Here, the type of transport is dependent both on national regulations as well as the components needing transport. In countries where Volvo Cars ability to influence the type of truck used for the last mile distance, an efficient transport is difficult to ensure, resulting in potentially larger emissions.

As we're in the midst of the electrification era, it's also likely that in the future, Volvo Cars transports will be with electric trucks. If so, significant CO_2 savings from transport could be made if the electricity mix is green, where emissions from road transport could approach zero if using 100% renewable energy for charging.

6.3 Cost discussion

For the costs, a similar trend can be seen as for the CO_2 emissions, i.e., components are the driving factor.

The last mile delivery costs are significantly higher than the cost of transporting a battery from the CDC to an LDC, this even though the CDC-LDC distance is much larger. This is partly due to the fact that Volvo Cars owns the entire transport from the CDC to the LDCs but they do not necessarily own the last mile transport. For example, Volvo Cars needs in some cases to contract a freight company with a special permit for transporting HV batteries. This highlights the importance of focusing on efficient transports for the last mile delivery.

Looking at figure 5.4 one can see that for the minimum scenario, the transports makes up the largest cost. However, the total costs for this scenario are small. In the maximum scenario, the components make up the largest part. The transport costs are generally low if looking at the total repair costs. If the battery packs would be transported alone, i.e., less efficient use of volume in truck, the transports could make up a much larger share.

The total cost of the repair is the same as the LCC. In the LCC, only costs that are accounted for in the emission analysis is included, i.e., no cost for end-of-line testing and logistics handling. Using LCC makes for a good comparison between the emissions and costs for the scenarios. However, it is important to note that are additional costs and emissions associated with end-of-line tests and logistics, but they are outside the scope of the thesis.

Looking at the savings from the repair scenarios in table 5.7, the same trend as for the CO_2 emissions can be seen, namely that repair is beneficial in all the studied scenarios. Just as for the emissions, the result is dependent on the in-going parameters and the fact that there might be additional costs that are not included in the calculations. However, it is cost-efficient to transport a BEV battery to the battery center and repair it and then use it in a vehicle again under these conditions.

Regarding recycling and repurposing in relation to costs, some interesting discussions are possible. For recycling, savings are possible from the recovery of these materials, increasing the profitability. For example, it is possible to recover up to 99.99% of lithium through the recycling process and a significant cost saving is possible due to the high price of lithium (Pagliaro & Meneguzzo, 2019). The savings are, once again, dependent on whether Volvo Cars can utilize the benefits from the recovery. Repurposing can provide cost benefits as well, mainly in two ways. First, it can support in depreciating the cost of the battery over a longer lifetime. This is beneficial here due to the high price of a LIB pack. Secondly, it can provide cost benefits during its second-life application. If it is used as a grid storage, it can help to support the grid or a facility during its peaks and thereby lowering the electricity costs.

An additional benefit for all three circularity alternatives is the cost savings associated with the potential rise in commodity prices for scarce metals such as lithium, nickel and cobalt. A decrease in price for lithium and cobalt could be seen for the latter half of the 2010's but a sudden and drastic increase was observed in 2021 (USGS, 2022a, 2022b). For nickel, the price has been increasing steadily for the past years, reaching a record level in 2022 (USGS, 2022c). To support the ramp-up of EV production, big investments went into the lithium and cobalt industry in the mid 2010's. In recent years, an expected increase in the interest of EVs has been seen, partly due to the new climate-related goals of many automotive manufacturers. This increased demand has led to a concern for the ability to supply the materials and resources needed for production, and by that, driving up the prices of these commodities (Fastmarkets, 2021). Another concern is that these metals are extracted in a limited number of countries, increasing the risk for price volatility and supply chain disruptions (Van Hakm, 2022). Here, repairing, repurposing and recycling will play a crucial role in order to keep these materials in the loop and by that releasing the pressure on the commodity market and managing the risks of price volatility and disruptions.

6.4 Repair scenario analysis

From the repair scenario analysis, it is clear that large CO_2 savings are possible when repairing a battery in comparison to replacing the entire pack. Looking at the results from the min repair scenario, the CO_2 savings are just over 11 070 kg of CO_2e whereas for the max repair scenario it is about 1 000 kg CO_2. This shows that even if every component possible is repaired and all transports are included, it is still worth it to repair the battery from an emission perspective. Furthermore, only the cell module data is specific to the battery pack under investigation whereas the other components are modelled from external data on a battery pack of a different capacity (Ellingsen et al., 2014). For the future, it's important to secure good and reliable data for every pack component through LCA. This should be prioritized by Volvo Cars in order to get the full picture of the emissions from the BEV battery pack. Decreasing the emissions per module is crucial in order to influence the total pack emissions and thereby the carbon footprint for a battery pack in a BEV. Efforts to decrease the emissions per module include for example changing the switching to a cleaner electricity mix in the production or producing at a site with greater capacity and thereby higher efficiency.

Looking at the emissions per km and the results from figure 5.3, it shows that the CO_2 savings are largest in the beginning of the pack's lifetime and then rapidly decreases towards the end of the lifetime. This is because, the later in the lifetime of a battery pack the repair is conducted, the less is the remaining distance the repaired can create value. This is naturally dependent on the assumption of 200 000 km for the specific pack under investigation. However, there are always savings connected to the repair process throughout the full lifetime of the pack according to these results.

6.5 Sensitivity analysis

In order to test the robustness of the results and how they would change if with in-going parameters, a sensitivity analysis was conducted. In this section the results and discussion from this analysis is presented.

6.5.1 Last mile delivery distance impact on transport emissions

Because a last mile distance of 200 km is assumed in this study, the assumption is tested by varying this distance and observe the effects on the resulting CO_2 emissions for the total transport. An additional assumption is that the last mile delivery is done with a truck of the same model and therefore same emission factor, as the truck driving between the CDC-LDC. In reality, there will be varieties in which type of truck is used for the last mile distance. To test this assumption, three different emission factors are tested for the last mile distance.

In figure 6.1, the total CO_2 emissions from transport are displayed for the common scenario, along with the emissions from the last mile distance.

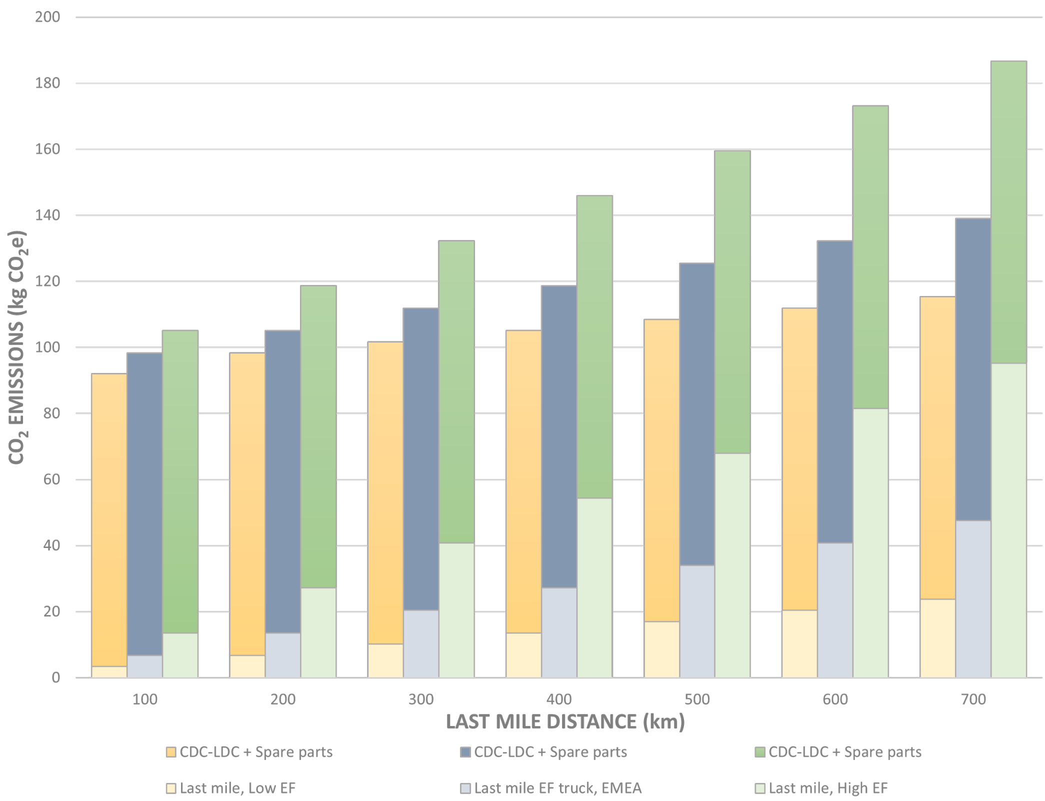

Figure 6.1: Total CO_2 emissions (kg CO_2e) from transport presented over a varying last mile distance- on the x-axis, each with three different emission factors, namely $EF_{truck,EMEA}$, Low EF (x0.5 $EF_{truck,EMEA}$) and High EF (x2 $EF_{truck,EMEA}$)

Figure 6.1 shows that the assumption of the distance for the last mile delivery has an impact on the total emissions generated from that distance. The higher the last mile distance, the higher its share of the total transport emissions. At lower distance, the last mile has a very low impact on the total emissions, whereas at a last mile distance of 700 km, the last mile distance make up 21%, 34% and 51% percent of the total transport emissions respectively, depending on the emission factor.

As the transports (given $EF_{truck,EMEA}$) make up 13% of the total emissions for the common scenario, the last mile delivery associated emissions in the case of a last mile distance of 700 km only accounts for about 4% of the total emissions. They can therefore be judged as not effecting the end results significantly. For a last mile distance of 200 km, the impact will be even lower. Therefore, the assumption regarding a last mile delivery distance of 200 km and $EF_{truck,EMEA}$ can be considered reasonable.

6.5.2 Electricity mixes' effect on emissions from aluminium manufacturing

Looking at the aluminium carrier, a significant difference in CO_2 emissions related to the manufacturing can be seen depending on the used electricity mix for powering the production on site. The higher the fossil fuel share in the electricity mix, the higher the total emissions per kWh output to the production processes.

In this thesis, the aluminium for the carrier is assumed to be extracted and produced in China. Through Ecoinvent, data was collected for aluminium production in Europe and China (see table C.1 in appendix 4.3). For two out of three processes included in the aluminium production, values for China exclusively was not available and instead an average of China with the rest of the world (RoW), excluding Europe, was used. It is clear that the aluminium production in China emits more than the corresponding process in Europe. One explanation to this could be the electricity mix used in the production. It is common for large aluminium plants worldwide to generate electricity from its own power plant, and given the values from Ecoinvent, it can be assumed that plants in China use fossil fuels to generate power to a higher extent than in Europe.

The results from the comparison of aluminium production in China vs Europe can be found in table 6.1.

Table 6.1: Total emissions from aluminium production depending on the location of production given in kg CO_2/kg aluminium.

Location	**Production emissions [kg CO_2/kg Al]**
China/RoW	38
Europe	21

The resulting CO_2 emissions from aluminium production in Europe is almost half of those produced in China, as can be seen in table 6.1. This illustrates the impact that the electricity mix has on the emissions from the aluminium production and on the total emissions from a battery pack. In addition to this, it indicates the importance of using a greener electricity mix to lower the emissions further.

In figure 6.2, the total CO_2 emissions for a battery pack is shown for aluminium production in China vs Europe.

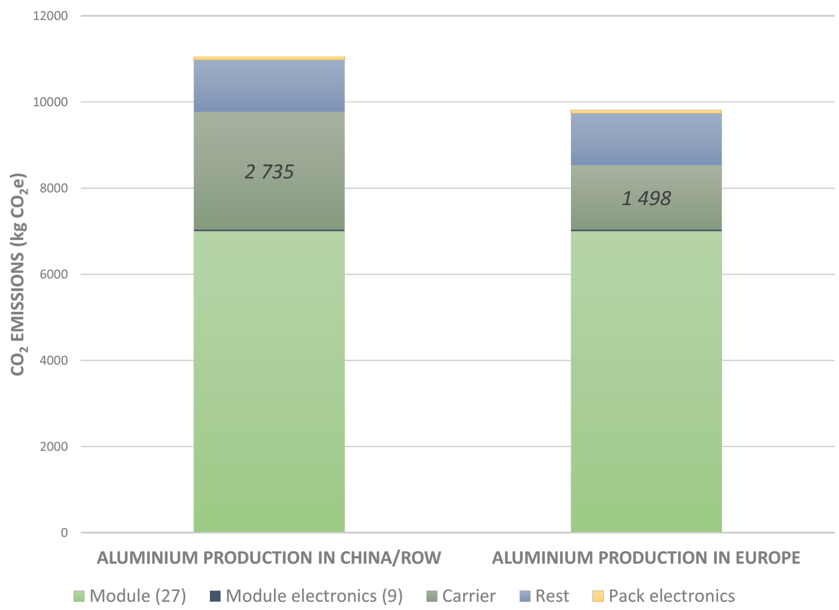

Figure 6.2: CO_2 emissions for the complete battery pack depending on aluminium production in China/RoW or Europe.

The total CO_2 emissions for the specific battery pack under investigation, where the aluminium carrier would be produced in China vs Europe, is 11 050 kg CO_2e and 9 800 kg CO_2e respectively. This indicates a CO_2 emission decrease of about 11% for the entire pack if production and processing would occur in Europe instead.

6.5.3 Battery cell modules' impact on total emissions

As emissions from cell modules can vary, the question whether it is beneficial to repair or not can be affected. Looking at table 6.2 below, the cell module values from this study are compared to one that is x2 and x0,5 its size respectively.

Table 6.2: Sensitivity analysis for cell module data impact on total pack emissions, with varying emission values per module.

Parameter	Module emissions
This study	90 kg CO_2e/kWh
x0.5 module emissions	45 kg CO_2e/kWh
x2 module emissions	180 kg CO_2e/kWh

In figure 6.3 below, the cell module emissions for the two different values are compared to the emissions from this study and are divided between the modules and the other components.

The blue part of the bars represents the emissions from the cell modules scaled using the three different values. The green value represents remaining components and is the same across all options.

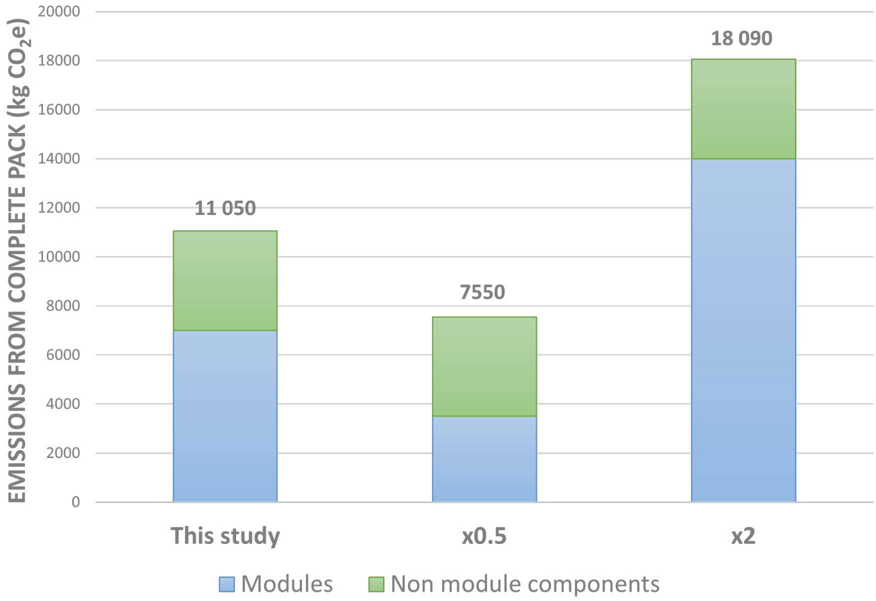

Figure 6.3: Emissions from cell modules as a share of total emissions in this study compared to modules emission values x0.5 and x2 the size.

As can be seen in figure 6.3, the modules make up a major part of the total emissions for one pack, about 60%. It is of interest to observe the influence of changing the emission value per module on the results. Here, we observe an increased (x2) and decreased (x0.5), relative to this study, emission value per module. For a x2 emission value per pack, the modules make up 78% of the total pack emissions, whereas for a x0.5 the emission value, the modules make up 46%. The total emissions from the common scenario in this study is 690 kg CO_2e and for the x2 and x0.5 scenarios, the values are 1200 and 430 kg CO_2e respectively. Looking at the CO_2 savings in percentage from the common repair scenario for the different module emissions (x1, x2 and x0.5), they show similar values 93,8%, 93,3% and 94,3%, indicating that changing the emission value for the modules within a reasonable range, does not in fact influence the relative size of the CO_2 savings for the studied scenario. This indicates that the results from this study are robust, and that repair from a CO_2 perspective is motivated independent of module emissions and their share of the total emissions.

However, it is important to note that in absolute values, the same cannot be said. Increasing the emissions from the modules will increase the total emissions for the battery and by that also increasing the absolute emissions from the repair. When you double the module emissions, the total emissions of the pack are 1.6 times the original value. This is because the total emissions for the pack are so dependent on the contribution of the modules, if they were less dependent (had a lower share), the effect of the changed modules would be lower.

As the emissions for cell production decrease with greener production, the modules share of the total emissions will decrease and naturally and the share of the non-cell components of the pack will increase. Northvolt has set up as a goal to reach 10 kg CO_2e/kWh in 2030, this will have a positive effect on the total emissions from the battery and will be of benefit to Volvo Cars through their joint venture (Northvolt, 2022; Volvo Cars, 2022f). Given that the non-module components will have the same carbon footprint, the carrier will make up 57% percent of the total emissions and this means that these "remaining" components will stand for most of the emissions and will be the ones needing a lower carbon footprint to motivate EV production and decreasing the climate impact. In order to reach this, Volvo needs to conduct extensive LCA's on the other components as well.

6.5.4 Last mile distance costs' impact on total transport costs

As can be seen in table 4.8, the last mile delivery costs are the largest of the transport costs within Europe. In figure 6.4, three different cost scenarios are presented, the current last mile delivery cost, a cost that is x2 and one that is x0,5 its size.

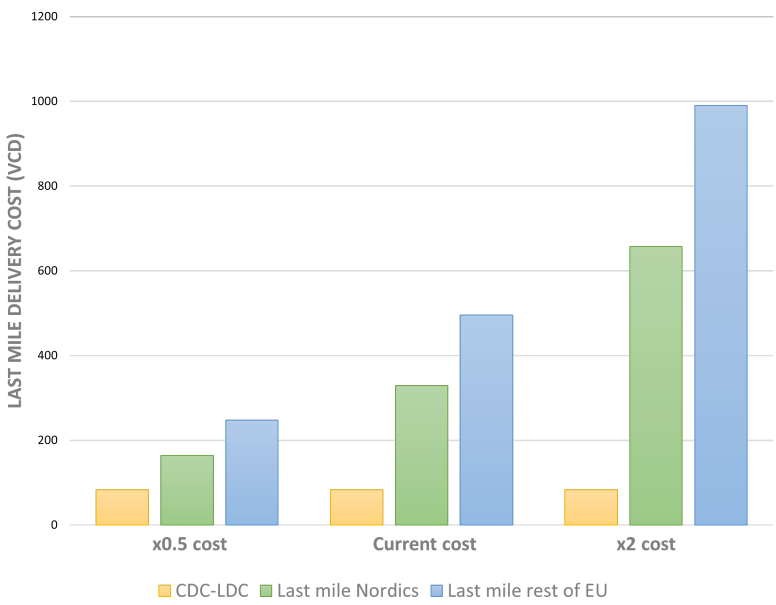

Figure 6.4: Cost (VCD) for the last mile delivery in the Nordics vs in the rest of EU. The last mile delivery cost is displayed as the current and as x0,5 and x2 the size of the current cost.

It is clear from figure 6.4 that the last mile cost has a major impact on the overall transport costs. However, as can be seen in 5.4, transports rarely makes up the largest portion of the total costs. To affect the profitability and cost savings for the transport, efforts should be focusing on the last mile delivery. Here Volvo Cars needs to increase their influence on the complete supply chain and focus on the last mile delivery. This to secure efficient transports, both from a cost perspective and from an environmental perspective. Focus should also be on making sure that no or as few batteries as possible are transported alone. This will allow for a higher utilization of the trucks and by that lowering the cost and emission per pack.

6.6 Future outlook

Below, two future outlook topics are presented, namely pack architectures and the concept of a centralized battery repair.

6.6.1 Modules vs cell-to-pack

The question about whether module-to-pack or cell-to-pack is the most beneficial option in terms of environmental load is rather discussed. On the one side, there are benefits related to repairing a BEV battery compared to producing a new one, as the results show in this study. This highlights the importance of designing battery packs in a way that allows them to be repaired. In this aspect, the module-to-pack solution has an advantage over cell-to-pack where it in the latter case is not possible to repair individual cells. An additional benefit of the module-to-pack architecture enables repurposing to a somewhat higher extent. The fact that modules are separate units allows for disassembly of the pack and the use of specific modules for different second-life applications. Assuming a similar failure rate of the battery pack as today, a cell-to-pack design will increase the emissions significantly. This because repair of a cell-to-pack pack is not viable and therefore, if a few cells are broken and needs to be repaired, the full pack would need to be exchanged which is associated with the emissions from producing a new pack i.e. 11 050 kg CO_2e. On the other hand, the benefits from the repair will only occur if the battery actually fails. This is difficult to predict to a precise degree. As the technology develops, the reliability of the batteries will likely increase. Accidents and unforeseen events will still continue to occur and can have an impact on the number of batteries that will need to be repaired. For the cell-to-pack, it’s important that the pack emissions are relatively low but also have a low failure rate. This combination would be beneficial.

The same goes for the cost, where the cell-to-pack technology would lead to higher costs when repair is no longer possible and a new pack has to be purchased. Especially when a rather inexpensive component, such as the electronics, needs to be repaired due to either component failure or an unforeseen event. This failure could lead to that the entire pack needs to be exchanged for a significantly higher cost than the cost of the repair. This is highly dependent on the architecture of the pack, something that (Cong et al., 2021) confirms. As shown in 5, large cost savings are possible when looking at all repair scenarios, this again highlights the importance and benefits of repair compared to producing a new battery.

The theory regarding the benefits of the module architecture was tested using linear optimization. The objective was to optimize the emission function for a certain failure rate or R/1000 (repairs per 1000) for the common scenario. Justification of non-repairability is dependent on the total pack emissions as well as the pack failure rate. In general, if non-repairability is to be justified, it requires a lower R/1000 value or lower total pack emissions respectively for the cell-to-pack architecture vs the module-to-pack architecture. The actual values are dependent on chosen input values both for total pack emissions and for R/1000. In reality, a combination of the two factors would be optimal.

6.6.2 Central vs local repair

A discussion can also be made regarding whether the batteries should be repaired locally at the dealer workshop (decentralized) or at a Volvo Cars battery center (centralized). Centralizing the battery repairs does not necessarily mean that there would only exist one battery center, in fact there can be one per region or even a few per region, however repair would not be performed at the workshops. A benefit from repairing at the workshops are the elimination of the transports from the workshop to the battery center whereas a benefit from using central repair is more control of the repair quality. Currently, the methodology used at the workshops are not as developed as the ones used at the battery center. A central control would make it easier to control the methodology, educate technicians and follow it up. A lack in methodology can lead to an increase in damaged components during the repair. However, it is likely that once the volumes of faulty BEV batteries increase, the workshops would gain more experience and perform repairs with a higher quality. There are also some components that cannot be removed at the workshop without damage, whereas at the battery center this can be done. A consequence here is that additional components that were not initially part of the repair needs to be repaired as well, increasing the total CO_2 load of the repair. In addition to this, instead of sending spare parts to the CDC, they would have to be sent to each dealer, increasing the complexity of the supply chain as well as the emissions.

As can be seen in figure 5.2, the share of emissions from the transport is rather low (note that this includes transports for spare parts, something that is needed for repair at the workshop as well), so the savings from repairing at the workshop due to elimination of transports are limited. This potential saving will also continue to decrease as the ramp up for the electrification of the truck transport fleet increases.

Along with potentially increased emissions due to the need of additional components and transport of all spare parts, costs will most likely increase as well. This is something that can lower the profitability of the repair. Purchasing the specific equipment for repair and end-of-line test would also be required.

To summarize, the risk of increasing both emissions and costs when conducting decentralized repair at the workshops is high. Central battery centers can therefore be justified under the current conditions. To change this, a strong centralized methodology including a standardized equipment would be necessary at the dealer workshops. This could become beneficial when the battery volumes increase and by that increasing the emissions associated with transports.

7 Conclusion

The manufacturing related emissions of the Li-ion battery under study are high, 11 tonnes of CO_2e, where the cell modules make up 63%. For the repair scenarios, the components are clearly the drivers of CO_2 in the pack. In addition, all the repair scenarios investigated show savings of CO_2 emissions in comparison to a full pack exchange. This indicates that battery repair is beneficial from an emissions perspective when the alternative is exchanging the pack for a new. For the transport related emissions of the repair scenarios, they make up a rather small fraction, staying in the 2-digit (kg CO_2e) range. However, with an increasing BEV population on the market and an increased need for battery repair, transports should not be considered negligible.

Similarly, all the repair scenarios investigated show cost savings in comparison to a full pack exchange. The significant savings are due to the relatively low costs for the technicians and for the transports, indicating that it's always beneficial to send a battery pack to the battery center for repair, from a cost perspective. The transport costs make up a small fraction of the total costs. However, the last mile delivery i.e. the last 200 km, make up a clear majority of the transports costs, often due to Volvo Cars buying this service from a local distributor. In order to keep the transport costs down as battery transport increases, focus should be on increasing the influence of the entire transport chain and to ensure co-transport of batteries.

This study shows that, given the current failure rates, designing and producing battery packs that are repairable is crucial from an environmental as well as cost perspective. This because non-repairability results in full pack exchange as soon as a fault appears and the manufacturing of a pack is associated with high emissions. In addition to environmental load, non-repairability will also limit the options for a potential second-life application. To gain benefits from a cell-to-pack architecture, the failure rate and manufacturing emissions needs to be low enough to justify the manufacturing of a new battery pack. Unless this can be ensured, a modular battery architecture is key in order to lower the lifetime emissions and increase circularity.

A centralized battery repair can be justified with different arguments, 1) the transport emission load is generally low, indicating that transporting the battery to a battery center has low contribution, 2) the quality of the repairs and standardized methods can more effectively be ensured and 3) multiple spare parts do not have to be transported to dealer workshops.

Looking forward, it is important for Volvo Cars to further investigate and quantify emission data with a higher level of detail for the battery pack and all its components. This in order to minimize uncertainty, identify action areas and to have a full overview of the environmental loads and their contributions to a BEV battery pack. Furthermore, reducing the environmental impact per BEV battery pack is crucial. This can be expected when cell manufacturing increases the use of electricity generated with renewable energy, such as in the case with Northvolt and their gigafactory in Northern Sweden. As efforts are put into reducing the CO_2 impact for modules, other non-module components e.g. the aluminium carrier should overseen to ensure alignment with CO_2 reductions to lower the overall emissions.

Lastly, the increase of repair and EOL management for BEV batteries will be crucial for Volvo Cars in order to increase EV circularity and maintain their recognition as a premium EV brand.

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A

Map of Volvo Cars local distribution centers in Europe

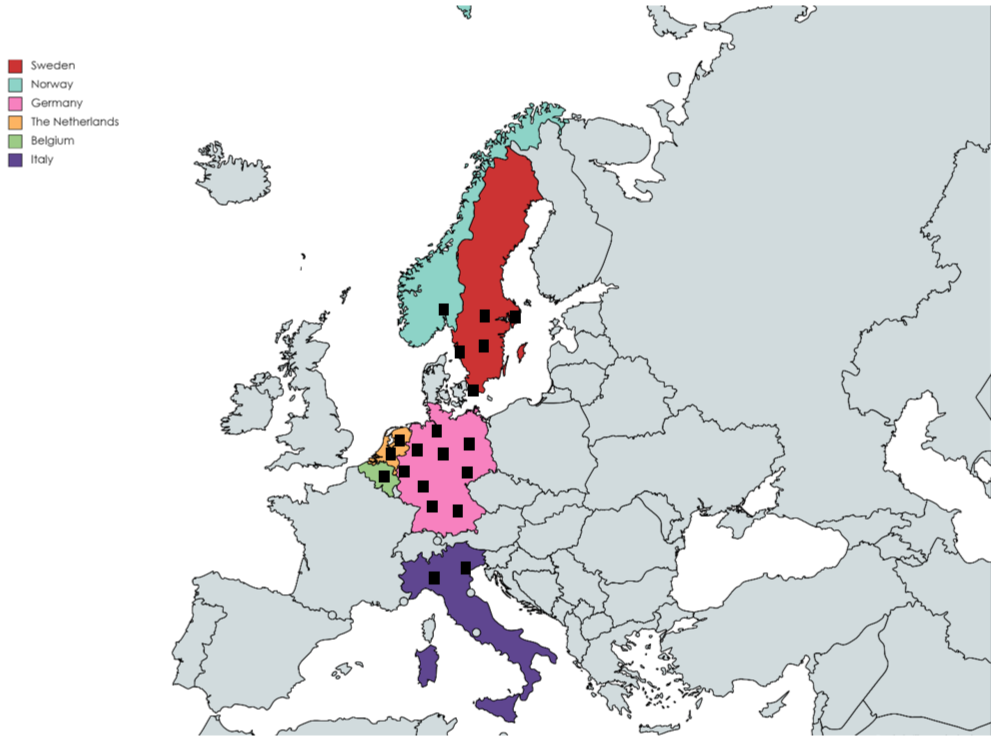

Figure A.1: Map of countries in focus, black squares represents one LDC

B

Map of supplier locations

Figure B.1: Map of supplier locations in China

C

Table of aluminium production emission data sets

Table C.1: Data depending on the location of the aluminium production from EcoInvent

Value [kg CO_2/kg]	**Data set**
23,6	'aluminium production, primary, ingot - CN - aluminium, primary, ingot'
13,4	'aluminium milling, average - RoW[a] - aluminium removed by milling, average'
0,98	'impact extrusion of aluminium, 1 stroke - RoW - impact extrusion of aluminium, 1 stroke'
38	**Total emission China/RoW**
7,3	'aluminium production, primary, ingot - IAI Area, EU27 & EFTA - aluminium, primary, ingot'
12,8	'aluminium milling, average - RER[b] - aluminium removed by milling, average'
0,71	'impact extrusion of aluminium, 1 stroke - RER - impact extrusion of aluminium, 1 stroke'
21	**Total emission Europe**

[a] Rest of the World & [b] Europe

D

Repair times in Battery Center at Volvo Cars

Classified, unpublished

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