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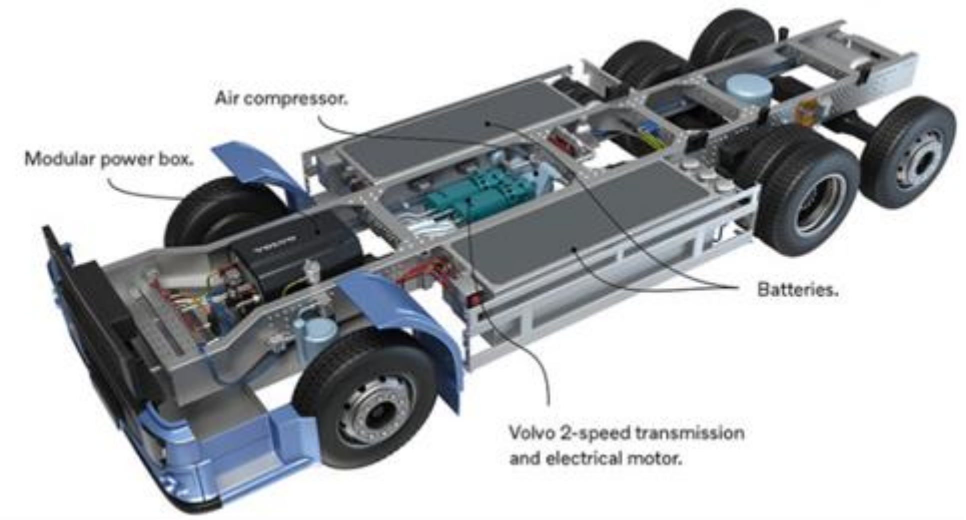

Design for Assembly and Disassembly of Battery Packs

Master's Thesis in Product Development

Mikaela Collijn 931215
Emma Johansson 920728

Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

MASTER'S THESIS 2019

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A collaboration between Chalmers University of Technology and Volvo Group Trucks Technology

MIKAELA COLLIJN

EMMA JOHANSSON

Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
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M. COLLIJN, E. JOHANSSON

Master's Thesis 2019:01
Examiner: Dag Bergsjö,
Supervisor: Amer Catic
Department of Industrial and Material Science
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone: +46 (0)31-772 1000

Cover:
Illustrating Volvo FL equipped with batteries and electrical engine. (1)

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Göteborg, Sweden 2019

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Abstract

Batteries are an upcoming and important part of future solutions for CO_2-neutral vehicles in society. To become more environmental friendly, Volvo wants to exchange the combustion engines with electrical engines and replace the liquid fuel with batteries. Adding a part to a vehicle means it must be assembled as well as disassembled which results in a need for a product that is optimal for an assembly-line. A literature study is therefore conducted in this project to improve the understanding of methods including modularisation as well as Design for Assembly and Design for Disassembly. Batteries in general is also revised to get a better overview of what functions and parts are included in a battery in order to map its functions in an Enhanced Function-Means model. This model creates an image of how the functions and design solutions are connected to each other. Thereafter, benchmarking of internal and external batteries is performed by using the functions as guidelines, resulting in a variety of design solutions. The design solutions are assessed from an assembly, disassembly and modularity point of view to establish what solutions are of interest. Based on the evaluation, an “ideal” battery is developed with focus on the hardware, hence the housing, attachment of modules and wires, thermal system and battery management box. An assessment is made of the application of these high voltage batteries in Volvo and how design for second life should be considered. Conclusively, the results from the study describes what parts of a battery to revise for it to be easy to assembly and disassembly as well as suitable to modularise.

Keywords: Battery, Electric Vehicle, Function-Means Modelling, Modularisation, Design for Assembly, Design for Disassembly

Acknowledgement

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Nomenclature

ASS	All-Solid-State
BEV	Battery Electrical Vehicle
BM	Brand Modules
BMS	Battery Management System
BMU	Battery Management Unit
C	Constraint
CBM	Circular Business Models
CE	Circular Economy
CM	Common Modules
CMA	Common Modular Architecture
CSC	Cell Supervision Circuit
CSU	Current Sensor Unit
℃	Degree Celsius
DAQ	Data acquisition
DFA	Design for Assembly
DFD	Design for Disassembly
DFX	Design for X
DOD	Depth of Discharge
DS	Design Solution
EF-M	Enhanced Function-Means
EV	Electrical Vehicle
FM	Flexible Modules
F-M	Function-Means
FR	Functional Requirement
HV	High Voltage
HVIL	High Voltage Interlock Loop
I	Current
ICB	Is Constrained By
ICE	Internal Combustion Engine
IP	Intellectual Property
IPMB	Is Partially Met By
ISB	Is Solved By
IW	Interacts With
K	Kelvin
LIB	Lithium-Ion Batteries
LFP	Lithium Iron Phosphate
LV	Low Voltage
m	Meter
MSD	Manual Service Disconnect
NCA	Lithium Nickel Cobalt Aluminum
NMC	Lithium Nickel Manganese Cobalt Oxide
OCV	Open Cell Voltage
Ω	Ohm
PAW	Pulsed Arc Welding
R	Resistance
RF	Requires Function

SMU	Safety Measuring Unit
SOC	State of Charge
SOF	State of Function
SOH	State of Health
UPF	Ultraviolet Protection Factor
UWB	Ultrasonic Wedge Bonding
V	Voltage
W	Watt

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1
Introduction

This chapter introduces the problem statement and purpose of the project as presented by Volvo Group Trucks Technology and Volvo Group Trucks Operations, including the background to the problem. The delimitations, actors and stakeholders are also presented.

1.1 Background

Volvo Group Trucks Technology is a global heavy-duty truck manufacturer from Sweden, with headquarters in Gothenburg. Volvo is one of the largest truck manufacturers in the world with production in 15 countries. One of the core values of Volvo is environmental care and they are acting in creating a path to a more sustainable society. (2) Internal combustion engines (ICEs) used today need to be replaced by some other sort of propulsion, both to meet the goals set by the European Commission and to make sure that the negative trend of greenhouse gas emissions is reversed. The European Commission's goal for heavy-duty vehicles is to reduce the CO_2 emissions with 15% by the year of 2025 and 30% in 2030. In numbers, this means that between year 2020 and 2030, around 54 million tonnes of CO_2 need to be reduced, a number that is equal to Sweden's total yearly emissions. (3) The common attitude around the world has also changed to an environmentally friendly one where it is common to decline products if they do not fulfill eco-friendly requirements. For these reasons automotive original equipment manufacturers are turning to batteries to power the engines of electric vehicles (EVs). Batteries are energy storing devices consisting of electrochemical cells, used to power electrical machines with different levels of capacity. Lithium-ion based batteries have shown to be promising for EVs with their portability characteristics, high energy, power density and low self-discharge. (4) Therefore, battery electric vehicles (BEVs) powered by rechargeable battery packs, will not emit CO_2 during use and more specifically, up to 97% of the pollutant emissions can be reduced locally depending on the source of electricity (5). Apart from reducing the climate impact, an electric truck can result in a quieter urban environment and enhancement of transport efficiency (6). A key factor for succeeding in installation as well as recycling of battery packs is the ability to modularise the battery pack design to enable high level of configurability needed in commercial vehicles as these are highly customized for different customer needs and applications.

1.2 Purpose

The purpose of this master project is to capture and formalize knowledge about battery packs gained within Volvo and synthesize it with data published in public sources. The main questions to answer during the project are the following:

- What current battery pack solutions exists on the market?

- What are the important battery pack interface properties, *"the ideal battery"*, from an assembly and disassembly perspective to get the best modularisation?
- Is configurability traded off with other characteristics?

1.3 Objectives

The objective of this study is to examine the possibility of modularising battery packs in order to facilitate assembly and disassembly as well as handling during production and services included in the aftermarket. This is accomplished by construction of functional models of existing high voltage batteries, to create a foundation of knowledge and to examine potential interfaces for future modules.

1.4 Delimitations

- Focus is on heavy-duty commercial vehicles and high voltage batteries.
- EV batteries are typically divided in three levels namely pack-, module- and cell level. In this project the study will be limited to focus on pack- and module level.
- Concentration is on the hardware of a battery pack.
- Access information due high degree of confidentiality.
- The placement of the batteries on the vehicle is given and is not investigated.

1.5 Actors and Stakeholders

Chalmers University of Technology:
Examiner of the master thesis at the department of Industrial and Materials Science: Dag Bergsjö, Associated Professor (dagb@chalmers.se), +46 31 772 13 78

Volvo Group Trucks Technology:
Supervisor of the master thesis at Volvo Group Trucks Technology: Amer Catic, PhD (amer.catic@volvo.com), +46 31 322 72 07

1.6 Time Plan

The project started at the 21st of January 2019 and is aimed to be completed at the 14th of June 2019, as presented in the GANTT-chart in Appendix A.1.

2

Research Approach

Along with the increasing need of accelerated time-to-market for products, design tools and methods are of growing importance. By applying such methods, as for instance modularisation or design for excellence, it can result in shortening of development cycles and reduction of costs.

2.1 Modularisation

Modularisation is the breakdown of a system into building blocks, in so called modules. What distinguish these modules is that each one has a specified interface. (7) By implementing modularisation in an organization, it can provide advantages such as simplifying the process of new product development and product redesign and, ascertain that customer requirements are met contributing to customer satisfaction (8; 9). Additionally, it can contribute to the company to stay in the lead as customers' needs of diversity and complexity in the product portfolio keep growing, as well as the continuous reduction of product life cycles (10; 11).

2.1.1 Modular Product Platforms

Product platform, also called product architecture, is defined in many ways. One that is often used is "the scheme by which the function of a product is allocated to physical components" by Ulrich (12). A product is divided into two different elements: the functional- and physical element. The functional elements describe what the product does, meanwhile the physical elements describe the product's structure and hence, a function is performed by a physical element. Physical elements can be grouped into modules to enable for example, easy- assembly or disassembly. (12)

Modular product platforms consist of a product family sharing a set of common modules. Standardized platform elements are a structured way to manage the internal complexity in an enterprise. By employing it, the component variety can be diminished within a product family. Thereafter, by combination of modules to new products, multiple product variations can be developed in the normal development process with a faster time-to-market. Conclusively, modular platforms can contribute to up to 20% savings in cost and 30% in time and enhancement in quality. A summary of the modularisation issue is presented in Figure 1. (10; 11)

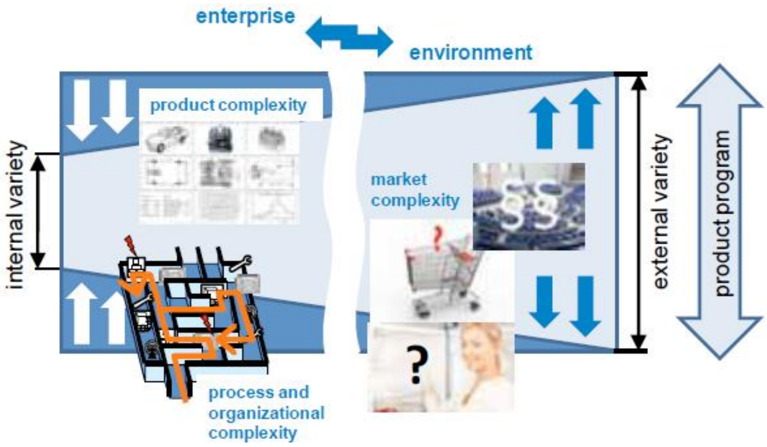

Figure 1: *Modularisation strategy* ***(11)***

2.1.2 Functional Modelling

In order to analyse a problem and find a solution to a concept, the functions of a product need to be defined (13). Functional decomposition and modelling list the primary functions and its sub-functions of a design. They contribute to open-mindedness as well as a systematic structure during the conceptual design process. Furthermore, it can be utilised as a tool for knowledge management in a way that the functional models store knowledge from existing designs that can be used in future product development projects. The definition of a product's functions can be done in a function tree where the functions are listed in a hierarchic manner. As a result, the requirements of the system can be graphically reviewed. (14) The tree can also include means in so-called Function-Means (F-M) modelling. Hence, not only are the functional requirements (FR) stated but also the design solutions (DS), the means, and the causality between the two. As Figure 2 illustrates, the main function is decomposed into several sub-functions and their respective potential means, allowing alternative solutions. (9)

The model can be divided in different levels depending on the degree of detail, more specifically in the static, conceptual, concrete and physical level as demonstrated in Figure 2. Initially, the static level contains the primary, upper level functions which are fixed. These are closely related to the company's business goals. Thereafter, in the conceptual level, the platform is broken down with various concepts as a result. The concrete level includes more defined and concrete functions and design solutions before the physical components are composited to a system in the physical level. (15)

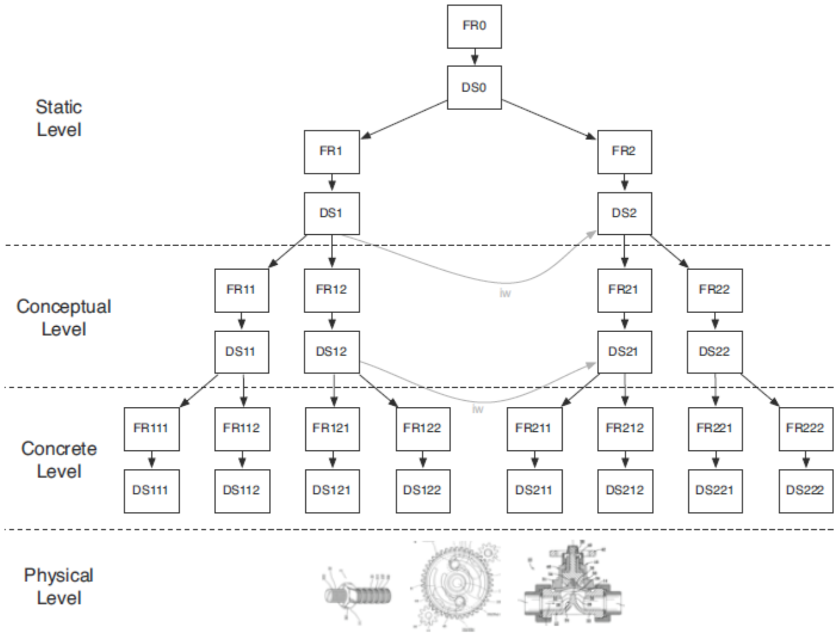

Figure 2: *Levels of a F-M model* ***(15)***

F-M models can also embrace the interactions both within and between systems, as well as outline constraints (C) concerning possible solutions. One example is Enhanced Function-Means (EF-M) modelling developed at Chalmers, as shown in Figure 3. Here, the design solutions need to comply with the functional requirement, "is solved by" (isb), as well as the constraints, "is constrained by" (icb) or "is partially met by" (ipmb). Additionally, each design solution requires a new functional requirement, "requires function" (rf), unless it is at the lowest level in the hierarchical structure. It could also occur that an alternative solution is a result of an interaction between two design solutions, modelled with "interacts with" (iw) in the figure. In this model however, the functions' relation to geometry and behaviour of the solutions are not included. Also, the physical and functional integration are not the same, each function has separate features. (16)

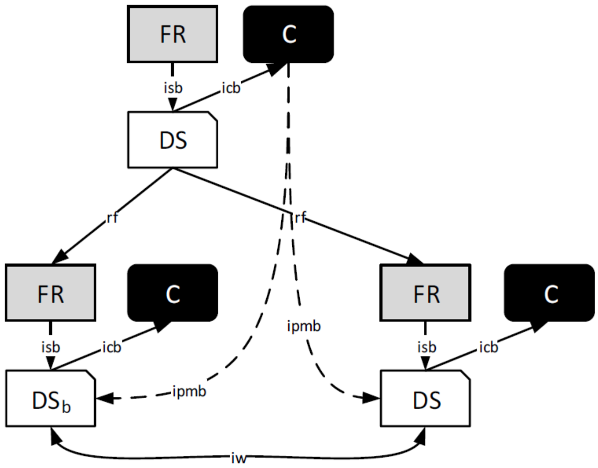

Figure 3: *An example of an EF-M model* ***(16)***

The process of using EF-M modelling to the purpose of redesigning a product is to first establish the primary functions and identify concrete solutions of the existing product. Thereafter, these DS should be connected to an FR on each level of the hierarchy. Once the model is outlined, new design solutions can be developed and replace the old ones, contributing to a new and improved design. (16)

With the help of EF-M modelling, it is possible to identify and place the batteries components in the right hierarchal order. This was done by carefully studying documents on batteries received from Volvo as well as published articles. The level that was in focus in this study was the concrete level due to it describing the functions and DSs in depth. The EF-M model generated a detailed overview of different functions solutions for which were found by benchmarking. It also showed how different DSs cooperates, although it did not describe any behaviour or geometrical solutions which means that the connection to structure is missing. An EF-M model is therefore good for finding what functions must be included and to create an understanding for what problems the functions should solve. Although, it tells nothing about how the product should look or behave. This resulted in a study of common batteries where it was crucial to separate FR from DS.

2.1.3 Common Modular Architecture

Interchangeable modules allow for commonality, customization as well as brand distinction. Developing product architectures with common modules and functionality connections is especially convenient in a multi-brand organization. In order to implement functional modelling in the industry, the tool Common Modular Architecture (CMA) can be applied in the early development phases. The approach was developed development between the industry and researchers from academia, designed to meet the company's requirements along with the customers' needs. The necessary inputs are technical regulations, information about requirements and CAD-drawings. The outcome is the functional models with design solutions, connections and constraints, as well as division of modules. The main elements in the CMA process are: (9)

- *Module* - Realisation of a function.
- *System* - Realisation of a high-level function, a group of modules.
- *Interface* - The interaction between modules and systems.
- *Platform* - A group of systems, where the modules have distinct interfaces.
- *Common Modules (CM)* - Is shared across brands and therefore, utilised in high volumes. These modules have standardized interfaces and one performance level.
- *Flexible Modules (FM)* - Have several performance levels conducing to product diversity, in order to satisfy dissimilar customer needs. These are also employed within different brands, using standardized interfaces.
- *Brand Modules (BM)* - Are brand-unique modules and hence, produced in low volumes.

To put CMA work into practice in an organization, a working team needs to be created and financially supported by the upper management in the company. Moreover, the company's employees need to be trained in CMA and make it a part of their daily work. The realization includes the phases illustrated in Figure 4:

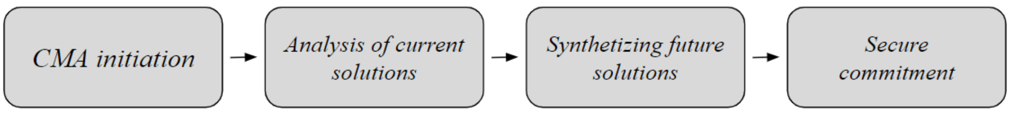

Figure 4: *Phases of the CMA process*

Firstly, the scope of the project and its requirements in addition to long-term technological roadmaps need to be determined and studied, to be able to introduce CMA to the project team. Next, a F-M model of the present system is generated by analysing current solutions and customer requirements, in order to establish a future F-M model and a modularisation strategy. Lastly, a CMA management report is finalized including both the strategy for modularisation and interface standardization as well as total system costs and potential investments of tools. (9)

CMA was initially considered to be used in the master thesis project but due to different circumstances such as limited access to information, it was decided to be left untouched. Despite this, it is still seen as a good method to be applied in future product development projects since it creates a stable foundation for the products. It is a method that facilitates a product platform that is beneficial for a company such as Volvo if given the right conditions to grow.

2.2 Benchmarking

Benchmarking is a method used to study current solutions available on the market as well as determine how far ahead the competitors are. A benchmarking study identifies where improvements are needed within the organization and forces it to find its competitive edges. It enables identification of new technologies which can be applied in new products later on, hence, it is a process that is ongoing and requires continuous updating. (17)

Benchmarking was performed on both internal and external EV battery packs with the help from questions raised during the EF-M modelling session. Researching EV batteries has its limitations due to confidentiality, especially when it comes to external batteries but also internal. Batteries are a confidential and strategic subject and the producers only give out limited information to some extent. Therefore the research has been relying on enthusiasts who, on their own, have studied the battery. The received internal information on batteries is better but still limited due to restrictions from the supplier, where a discussion is ongoing on what information can be transferred. Consequently, benchmarking was a challenging and time consuming method that in the end gave adequate results.

2.3 Field Study

To gain knowledge and receive information about real life experiences, interviews are an appropriate approach. By talking to people, it is possible to develop an understanding of the problem as well as gather information on how to reach a solution. There are two ways of receiving information, either by qualitative- or quantitative questions. In this project, the qualitative questions are in focus meaning that the questions are open-ended, and the interviewees are free to answer with their own words and can elaborate their thoughts without being interrupted. The structure of the interviews that have been performed are in-depth semi-structured interviews and enable the questions to be predetermined, with an interview guide that contributes to similar data being collected from all interviewees. A semi-structured interview is open and has the potential of exploring subjects outside the guidelines if needed, giving the interviewer the possibility to ask follow-up questions. (18; 19)

Interviews were conducted with nine people at Volvo during the project, where two of the interviewees were spoken to several times. The interviews gave a good insight to what was happening within the area of batteries, how Volvo is currently working with the subject and what kind of batteries are of interest. During the interviews the initial questions were adapted to the interviewee’s area of expertise to gain the most from the conversation and which was recorded with the interviewees consent. The interviews were a valuable source of information although when documents were requested, it was difficult for the interviewee to know if they had the authority to share it, resulting in limited access to information.

2.4 Design for Excellence

Design for Excellence (DFX) is a combined name for different methods that can be used in product development. It is a systematic way of working for designers who want to create the optimal product design. It provides the designers with different rules to follow and strategies to implement. DFX, such as Design for Manufacturing or Design for Assembly, give information and feedback regarding the design and therefore, help with improving the product from a certain perspective. (20)

2.4.1 Design for Assembly

By applying the method Design for Assembly (DFA) and making a product easy to assembly, it is possible to shorten the assembly time as well as minimise the number of parts. Consequently, this method reduces the cost of assembly and can improve the reliability and quality. DFA can be used in different kinds of assembly methods such as manual-, automatic- and robotic assembly, and it has a variety of techniques to evaluate how good an assembly is. To be able to make the most out of DFA, the method should be used during the entire product cycle, contributing to the possibility of decreasing costs. (21)

DFA was first considered after the benchmarking where the different batteries were shortly evaluated from a DFA point of view, to get an understanding of how the batteries might be assembled. The method was properly applied when a battery concept was examined and developed. By both looking at existing batteries and what DFA recommends, an ideal battery from the DFA perspective could be developed. This process only gave theoretical results which means that to find out if the solution is applicable in reality, further testing must be done.

2.4.2 Design for Disassembly

Design for Disassembly (DFD) is a relatively new method included in the design stage to enhance the disassembly of a product. This method has been in focus to a greater extent lately due to the environmental awareness in the society, and it can be divided in two different categories; total disassembly and selective disassembly. Total disassembly means that the entire product is taken apart into its constituent components, meanwhile the selective disassembly refers to disassembly of a complex product into non-complex single parts or subassemblies. Out of these two categories, the selective disassembly is the most common one since it enables repair and maintenance, material reuse and creates service parts out of the subassemblies. Here, the purity of the materials is also increased. Meanwhile, total disassembly is time consuming and not economically feasible. (21; 22)

Furthermore, when looking into easy separation, the different materials should be marked and parts that could potentially damage the machinery, should be avoided. For easy handling, it is important that at least one surface is accessible and that non-rigid parts are minimised since they can move. Finally, for easy disassembly the number of fasteners must be as low as possible and be easy to remove and the fractures, disjoining- and cutting points, needs to be easily accessible. Additionally, the material variety must be low since it enables simpler recycling and less complex movements. (21; 22)

DFD was applied at the same time as DFA, namely during both benchmarking and the development of the ideal battery. DFD and DFA goes hand in hand which means that the choice of how a part was assembled was also evaluated from a DFD perspective. It was discovered how important it is to think of DFD when remanufacturing and recycling are becoming a priority. The results given are still though only theoretical and further validation should be done.

3

Frame of Reference

A key element in an electric vehicle is the battery. The path from mining of raw material to the realisation of electric trucks on the road, illustrated in Figure 5, is a complex process. The battery itself consist of numerous different components and has several properties that is of importance and these are therefore further presented in this chapter.

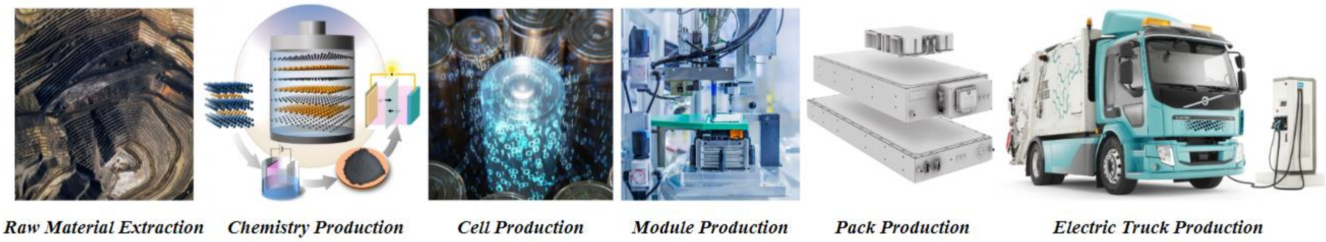

Figure 5: *Battery production process*

3.1 Battery Electric Vehicle

Compared to a traditional ICE vehicle, the powertrain of a BEV is an electric drive system containing an electric engine, an inverter, a central control unit and the energy stored in a battery. By changing the production to electric powertrains, the amount of parts is heavily reduced. (23)

3.1.1 Battery Cells

In battery electric vehicles, energy is stored in so-called battery packs that can be recharged. The packs' primary components are the modules, often connected electrically in series and constructed by a set of cells. These cells can either be cylindrical, prismatic or pouch as illustrated in Figure 6. (4) The electrolyte used in the battery packs varies depending on what kind of cell that is employed. A cylindrical- and prismatic cell utilises a liquid electrolyte meanwhile a pouch cell's electrolyte is made from solid plastic. These electrolytes are presented in Appendix A.2. (24)

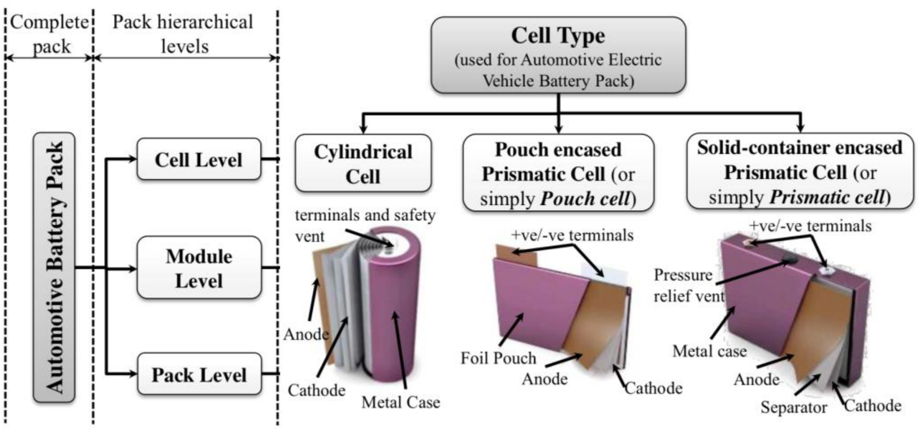

Figure 6: *Hierarchical levels of the battery packs and various battery cell types* ***(4)***

A comparison of the three different cells is presented in Table 1. The cylindrical cell has good mechanical stability, long life as well as good resistance towards deformation and heat dissipation. However, the cylindrical cell is inefficient from a packaging perspective. The pouch cell on the other hand, is efficient when it comes to cooling but has lower mechanical stability and deforms if the temperature rises. Finally, the prismatic cell has full space utilisation as well as a long life but has a medium resistance towards deformation. Today, all three cells are used in different kinds of electric vehicles although, there is a trend towards increased usage of prismatic- and pouch cells. Tesla for instance, uses cylindrical cells in their vehicles whereas BMW use prismatic ones. An automobile manufacturer that utilises pouch cells is Nissan. (23) Volvo has decided to move forward with prismatic cells in their electric trucks due to its characteristics of design flexibility, lifetime and mechanical stability. (23)

Table 1: *Comparison of the different cells* ***(25; 23)***

	Cylindrical Cell	**Pouch Cell**	**Prismatic Cell**
Energy Density	Low in module	High in module	Middle in module
Packaging Density	High	Low	High
Lifetime	Good	Medium	Good
Capacity	3-6 Ah	40 Ah	20-50 Ah
Housing	Metal	Soft-bag	Metal/plastic
Space Utilisation	Does not fully utilise the space	Space between every cell for possible swelling	Fully utilise the space
Design Flexibility	Low	High	High
Mechanical Stability	Tolerates pressure High stiffness High tightness	Swells Low stiffness Low tightness	Tolerates pressure Medium stiffness High tightness
Deformation	High resistance towards deformation	Low resistance towards deformation	Medium resistance towards deformation
Temperature	For cells with high capacity, the heat dissipation is low	Efficient cooling Good surface-volume ratio	Good surface-volume ratio

3.1.2 Battery Components

To prevent the battery pack from failing and ageing, a battery management system (BMS), a cooling system and a switch box are installed. The BMS controls the modules temperature, current and cell terminal voltage. The cooling system is utilised by the BMS to make sure that the cell temperature is within the recommended range and the switch box contains various monitors and sensors connected to switches, used to safely disconnect the battery when necessary. These systems are, together with the modules and the contact system connecting the cells to each other, packed in a housing with integrated interfaces to the product. The battery pack components are presented in Figure 7 and further explained below. (26; 27)

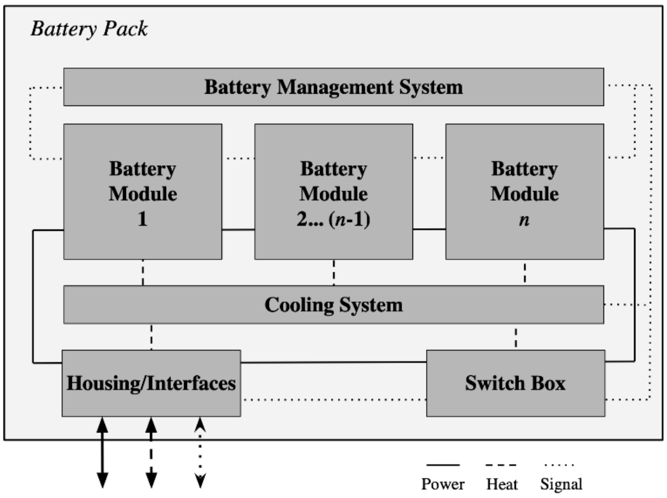

Figure 7: *Battery pack components* ***(26)***

Housing

The housing is the outer safety component of a battery with the functions of providing crash safety and prevent leakage. It is important that the housing is stable for the entire life of the battery as well as be of good quality, especially for the purpose of sealing the housing after assembly. Another important aspect of the housing is that it has good gripping points for the purpose of lifting it when mounting or dismounting it to the vehicle. (23)

Battery Management System

The Battery Management System (BMS) is the brain of the battery. It delivers the status of the battery capacity and health to the user, provides protection when limits are reached during charge/discharge or if failure occurs. Also, the BMS controls every part of the battery, monitoring and compensating for variation in cell parameters. All software that exist in the battery are incorporated here. (27; 23) In addition, the Battery Management Unit (BMU) is an electric circuit board included in the BMS with the assignment to control and monitor the battery. The BMU is connected to the vehicle via a controller area network and therefore, can communicate with the user. (28)

Contacting System

To connect the cells to each other, a contacting system is required. This system must be able to measure for instance, the heat impact and voltage on the cells and send the information back to the BMS, as well as assure a stable working process of the cells during the battery's life. (23)

Switch Box

The switch box holds switches, such as high voltage (HV) switches, which are used for disconnecting the battery from the vehicle, see Figure 8. The switch box has different sensors comprising; one current sensor monitoring the total current in the battery and one voltage sensor that evaluates the current sensor and communicates the results to the BMU. Moreover, there is an isolation monitor present that calculates the resistance between the HV terminal and ground as well as a mechanical fuse, protecting the battery from external circuit shorting. (26)

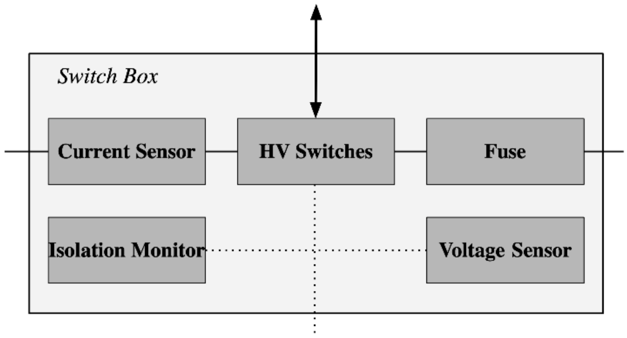

Figure 8: *Overview of the components included in the switch box* ***(26)***

Cooling System

The operating temperature of a battery should be within the limits of room temperature to obtain the best performance. Therefore, a thermal system is utilised to maintain the battery temperature within this interval. If a vehicle is driving in cold weather the battery needs to be heated. Consequently, cooling is required if the weather is hot. Heat is also released as a result of electrical losses inside the battery during use. (27) Furthermore, it is important that the temperature is not too cold during charging, to minimize the risk of it getting damaged. (28) Cold temperature increases the internal resistance and contribute to early cut-off (33). For the cooling system, a liquid coolant is normally used since air cooling requires big surfaces, which is not suitable for a vehicle battery. (27)

3.1.3 Battery Properties

In order to maintain a healthy battery, it is designed to keep properties as state of charge, health and function, in control. By managing the use of these and being aware of its status, both the manufacturer, service and user can prolong the life of a battery to a great extent.

State of Charge

State of Charge (SOC) indicates the level of voltage in a battery and the range goes from 100% when it is fully charged, to 0%, implying that the battery is empty. The recommendation from many manufacturers is to use the 80% depth-of-discharge (DOD) formula to rate a battery, meaning that the battery should have 20% energy left and not be fully charged or discharged, hence the practical limits for SOC are 20%≤SOC%≤80%. This is suggested since it increases the battery's service life. However, SOC is challenging to measure since the parameters; cell material, temperature and capacitance, all affects the voltage in the battery. (28; 29)

If SOC reaches a too low level, the battery is put under stress and the protection circuit opens. Consequently, the battery becomes unserviceable and unusable for the owner and cannot be charged with a regular charger anymore. (30) If the battery is overcharged, meaning that the charge exceeds the specified voltage for the battery, stability is lost, and gas is produced. If the battery continues to be charged at this point, a thermal runaway occurs and the battery bursts into flames. (31)

State of Health

State of Health (SOH) describes how well a battery works over time and is also known as the ageing of a battery. The main indicators that represent SOH are capacity, internal resistance and self-discharge. Capacity is the amount of energy as a function over time (28). Internal resistance represents how well the current can be delivered. Finally, self-discharge characterizes the stress-related condition and the mechanical integrity of a battery. (32) The first thing that affect the battery's SOH is the amount of charge that can be received, with Figure 9 showing how the capacity decreases during usage. In the figure, d_1 represents the capacity when the battery is new and d_2 the capacity after 200 cycles, indicating that the more the battery is used, the smaller the diameter. Even though the diameter and capacity have decreased, the displayed SOC value will be 100% charged. (28)

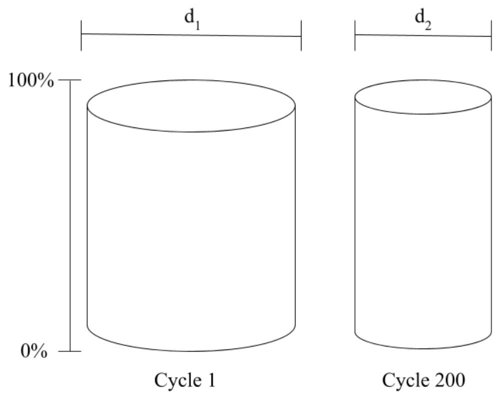

Figure 9: *Capacity represented by the diameter of a cylinder*

State of Function

State of Function (SOF) is defined as the ratio between the capacity and the remaining available charge in the battery and is thus, a combination of SOC, SOH, the charge/discharge history and the operating temperature. The method is used to analyse the readiness of the battery. (33)

Maintenance

Battery maintenance focuses on keeping the cells in balance, meaning that all the cells should be at the same level as the cell with the lowest voltage. Ideally, all cells have the same Open Cell Voltage (OCV) without any assistance but the reality is that each cell has its own specific voltage, see Figure 10. OCV relates to the amount of voltage a cell has when no current is going in or out of it. If one cell is discharged to a too low voltage, the cell cannot be recharged and hence, becomes unusable. On the contrary, if the cell would have a too high voltage, it will instead become instable and the risk for a thermal runaway is high. To avoid a too low or an excessively high level of voltage and make sure that all cells' voltage matches the cell with the lowest value in a pack, each cell has an individual discharge resistor. This resistor cooperates with the BMU who determines the target voltage and the BMU sends a signal to the resistor as soon as there is a change to restore the balance between the cells. (28)

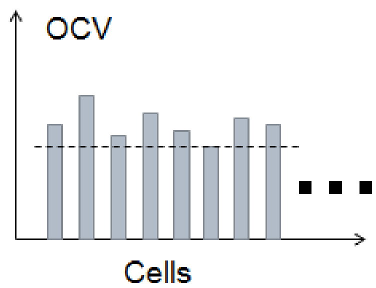

Figure 10: *Description of each cell and its open cell voltage* ***(28)***

Pre-charge

Pre-charge is used in the early stages of charging a battery, by creating a parallel pulse for the current through a resistor and is not included in the normal operation. The resistor makes sure that the incoming current is not too high and is designed to resist high temperatures, since high current enables this. Pre-charge also helps with preparing the battery’s temperature for charging, making sure it is in the range for optimal charge. (27)

3.1.4 Battery Chemistries

Battery cells can be made of various materials depending on the wanted outcome. The most common ones used for cells in BEVs are of the chemistry type lead acid or lithium-ion as presented hereafter.

Lead Acid Batteries

The basic structure of a Lead Acid Battery is made from lead alloy and it is a reliable, cost-effective battery with a low cost-per-watt base. Lead is mixed together with other materials, most common are calcium, selenium, tin and antimony, to increase the mechanical strength and improve the electrical properties since pure lead is too soft. Antimony and tin increase deep cycling, meaning that the battery manages to be discharged several times, and calcium reduces self-discharge. The downside with using a lead acid battery is its weight and the low durability when compared to lithium-ion batteries. Depending on the DOD, the battery only lasts for around 200-300 cycles due to corrosion on the positive electrode, growth on the positive plates and depletion of the active material. (34) The growth on the positive plate results in a need for equalizing charge, meaning that the battery is overcharged to remove the crystals growing on the plates. (35) Lead acid is not a fast charging battery, the time to fully charge a pack is around 14-16 hours, and it has a moderate life span. The positive aspects with Lead Acid batteries are that they work well in low temperatures and have good charge retention and are today, commonly used in starter batteries for ICE vehicles. (34)

Lithium-Ion Batteries

Lithium-Ion Batteries (LIB) are batteries where the anode is for instance Lithium Cobalt Oxide (LCO) and the negative terminal is graphite. (36) LIB are complex products that can for various reasons age too fast and become unusable. Some of these ageing mechanisms on the positive terminal are changes in the electrolyte, decreased accessible surface, gas evolution and corrosion, resulting in a power- or capacity fade. Meanwhile, the negative terminal’s ageing mechanisms consists of among others; corrosion and binder decomposition, leading to capacity reduction. (37) Moreover, LIB are sensitive against changes in temperature and the rate of ageing is accelerates if the temperature goes above 25˚C. Thus, it is important to have both a cooling- and heating system that keeps the temperature in a steady interval as Section 3.1.2 specifies. (38)

LIB batteries are common in EVs and one type that is often applied is the Lithium Iron Phosphate (LFP). This chemistry utilises phosphate as the negative terminal and consequently, has low resistance with good electrical performances. LFP has the benefits of having a long cycle life and a high current rating as well as good tolerance for abuse leading to enhanced safety. Disadvantages with this chemistry is the balancing issues that comes with ageing where self-discharge is high within the cells. (39) LFP is the chemistry that Volvo previously utilised in their battery packs but has decided to move away from. Another chemistry that is regularly used is the Lithium Nickel Cobalt Aluminum (NCA). It is a chemistry that offers high specific energy and power as well as a long-life span. The negative aspects with NCA are cost and safety with a high cost per kWh and high risk for thermal runaway due to a low maximum temperature (150˚C compared to 270 ˚C for LFP). (28; 39) The cell chemistry that is presently used by Volvo is the Lithium Nickel Manganese Cobalt Oxide (NMC), it provides high power and capacity and has a low self-heating rate. NMC has a maximum temperature of 210 ˚C and is sensitive to high charge which could cause thermal runaway. It also has a cycle life of 1000-2000 cycles (same as LFP) meanwhile NCA has around 500 cycles. (39)

3.1.5 Joining Methods for Prismatic Cells

Depending on which cell type (introduced in Figure 6) that is utilised in a battery pack, the electrical, thermal and mechanical requirements that need to be met vary. Therefore, when choosing the joining method, it is important to keep this in mind. In the pack there are both electrical and structural joints between the modules, containing mechanical, electrical, material, thermal and metallurgical joining challenges. Module- and pack joining of prismatic cells, the cell type used by Volvo, is to a great extent carried out using mechanical fastening methods including clip fitting, spring clasps or nut and bolt assembly, as Figure 11a display. It has a high joining strength and is easy to dismantle but contributes to high contact resistance. Other techniques that have been adopted are laser welding, pulsed arc welding (PAW) and ultrasonic wedge bonding (UWB), mainly for joining of cell terminals and bus bars. For laser welding, as Figure 11b shows, a small area is welded in a fast pace leading to the temperature staying at approximately the same level during the process.

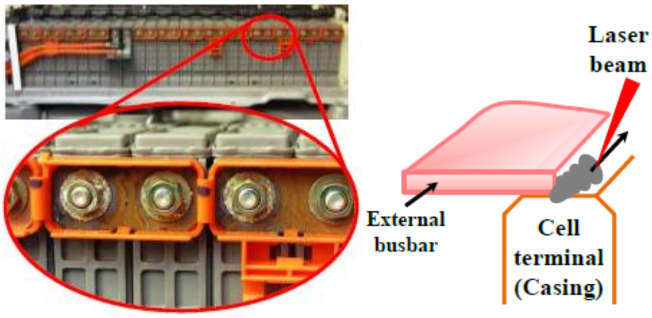

Figure 11: ***(a)*** *Nut and bolt assembly of prismatic cells (from Toyota Prius)* ***(b)*** *Laser welding* ***(4)***

PAW, in Figure 12a, use electricity and fusion to locally weld thin metals together by using a pulsed tungsten electrode. Because of the rapid pulses the heat input is reduced, nevertheless there is still a risk that the battery can be overheated, and the process needs to be continuously controlled. Welding using UWB is performed by ultrasonic vibrations that press a wire onto the target to join the materials, see Figure 12b. Although, to prevent the substrates from moving, since movement could reduce the amplitude of the vibrations and result in a decline of generated ultrasonic energy, they need to be placed in a fixed position, sometimes also by the help of adhesives. Both PAW and UWB can be used to join dissimilar materials. However, in relation to maintenance and service characteristics, permanent joining of the pack is not as suitable as mechanical assembly. (4)

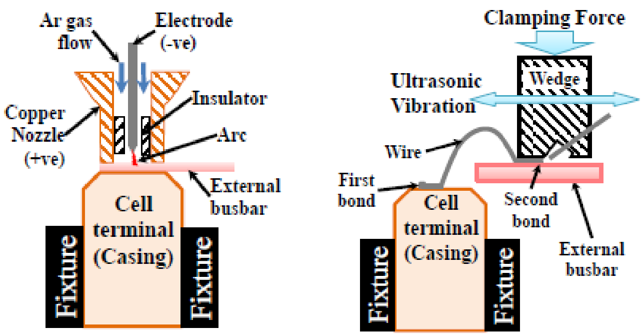

Figure 12: ***(a)*** *Pulsed arc welding* ***(b)*** *UWB* ***(4)***

3.1.6 Management of HV Batteries

Management of the batteries require special certifications because of its high voltage. Special training is compulsory for an operator to be allowed to handle the battery with a voltage of around 700 V, due to safety aspects. (27) Moreover, training is necessary for people involved in transportation of the batteries, such as loading, unloading, preparing for transport and transport outside facility area. The Volvo standard “STD 871-0003” account for operation of electrical installations in vehicles, concerning the personal safety requirements. It counts for the internal working environment, what the operators can do and not do when handling batteries according to national legislations.

The first step is to ensure safety by evaluating potential electrical risks of the operation and then, to assign suitable operators for the work with use of appropriate clothing and equipment. (40) This includes for instance tools, gloves, shoes and floor that is electrically isolated as well as equipment in case of fire or toxic gases caused by the electrolyte in the cells. (41) The risk assessment is executed by a skilled person. It is of importance that safety rules, regulations and instructions are continuously reviewed and that the personnel act in accordance with them. Furthermore, information essential for verifying safe operation need to be accessible and trustworthy, to prevent misunderstandings and accidents. There is a so-called nominated person responsible for each electrical installation and for each work activity. A nominated person also controls the personnel and is in charge of performing the connection activities; commissioning and decommissioning. Commissioning include the connection of the electrical installation to power while to decommissioning, disconnects the power source. The various roles and work locations for operations of electrical installation are demonstrated in Figure 13. (40)

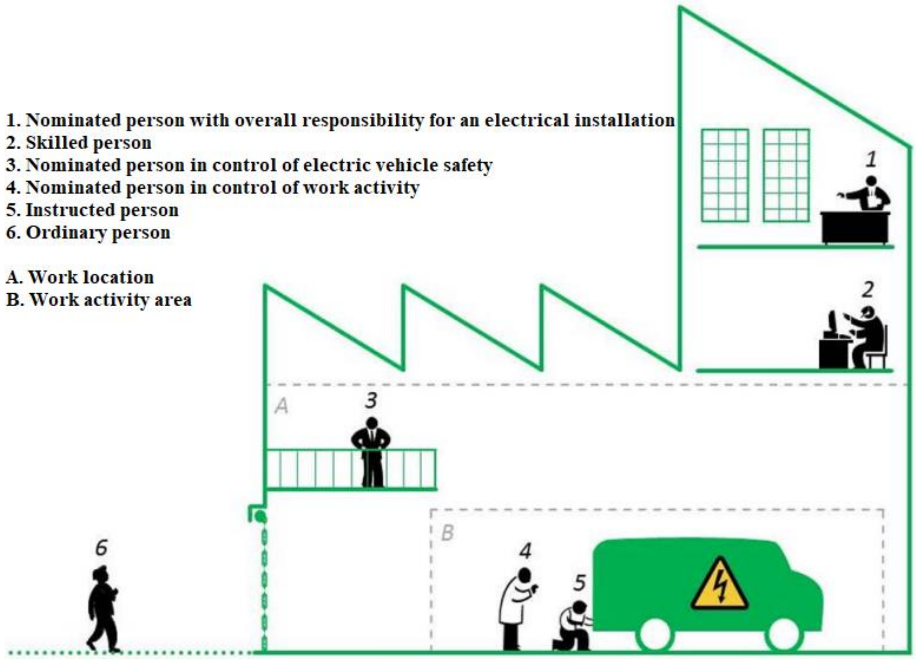

Figure 13:** Roles and work location at workplace for electrical installations **(40)

4

Results of EF-M Models

A battery is a complex product with many functions to achieve. These functions are important to display in order to find suitable solutions and combinations in the development of a working product. In this chapter, the functions are mapped and displayed in F-M models, complying with the method found in Section 2.1.2.

The main function of a battery is to store energy and to provide as an energy for a user whenever it is needed. To fulfill this requirement different sub-functions exists, including isolation of the battery, control of the system and energy conduction. These main functions can be seen in the EF-M model in Figure 14, where the grey squares are FR, the whites are DS and the constraints shown in black. The blue lines represent which design solutions that interact with each other.

There are two ways to isolate a battery, namely by constructing an outer casing that differs from the inner. Both DSs are important to consider and develop further since the battery itself needs to be protected from the surrounding environment but also the other way around, to protect the user and the outside environment from the harmful atmosphere and high voltage inside the battery. The function of controlling the system involves how the battery can be controlled, both from a usage- and safety perspective, and are solved with the help from hardware and software. Lastly, conducting energy refers to how the energy in the battery is stored and transferred. The storing is solved with the battery cells meanwhile the energy is transported through wires. Although, since the focus of the project is at the module- and pack level of batteries, these will not be further addressed. Cs on the battery pack relates to the given space on the vehicle, the volume, and the weight since the battery adds to the total weight of the vehicle. The DSs that interact with each other are the Outer- and Inner Casing with Hardware since they affect one another when a design change is made. Furthermore, Wire Management and Battery Cells connect with Software through the signal- and energy flow.

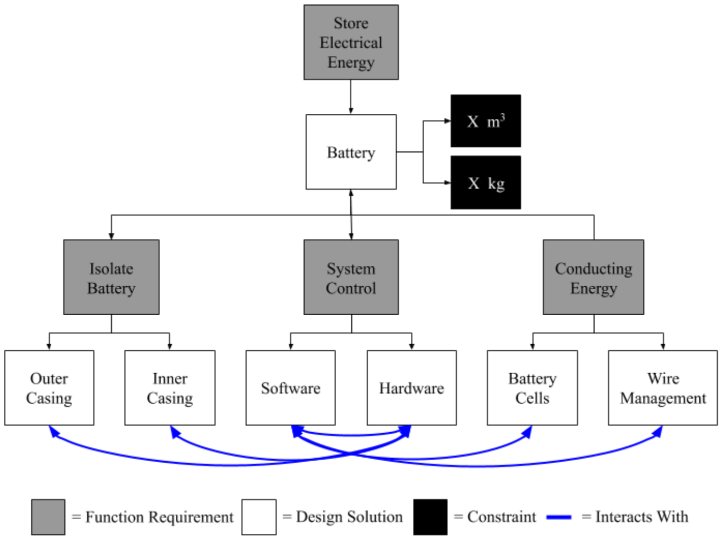

Figure 14: *Main function of a battery and its sub-functions including design solutions*

Figure 15 presents the Outer Casing and has three FRs it needs to accomplish. The first one is to maintain the internal environment. This is of importance since the cells are of delicate nature and demand a stable environment to function properly and by using a ventilation system, gases can be removed. The ventilation system is constrained by the amount of harmful emissions it can release from the gases as well as where the outflow is placed. Secondly, it is essential that the Outer Casing can withstand external violence, both in case of collision and the continuous vibrations throughout usage. These vibrations have the potential to harm the battery in the long term meanwhile, a collision requires the casing to protect the inside from instant substantial forces. It is important for these DS to meet the Cs, meaning that the Hard Casing must withstand a specific force before it is deformed. The same goes for vibrations and the Cs this have on the material, including a specific tensile- and yield strength. Lastly, the casing must withstand the surrounding environment such as temperature change (W/mK) or humidity (m^2), to maintain its inner environment for the battery to work properly. The Cs for these DSs involves how good the material can withstand ultraviolet rays and conductivity, and the area that must be sealed to make sure that nothing from the outside environment enters the inside of the battery.

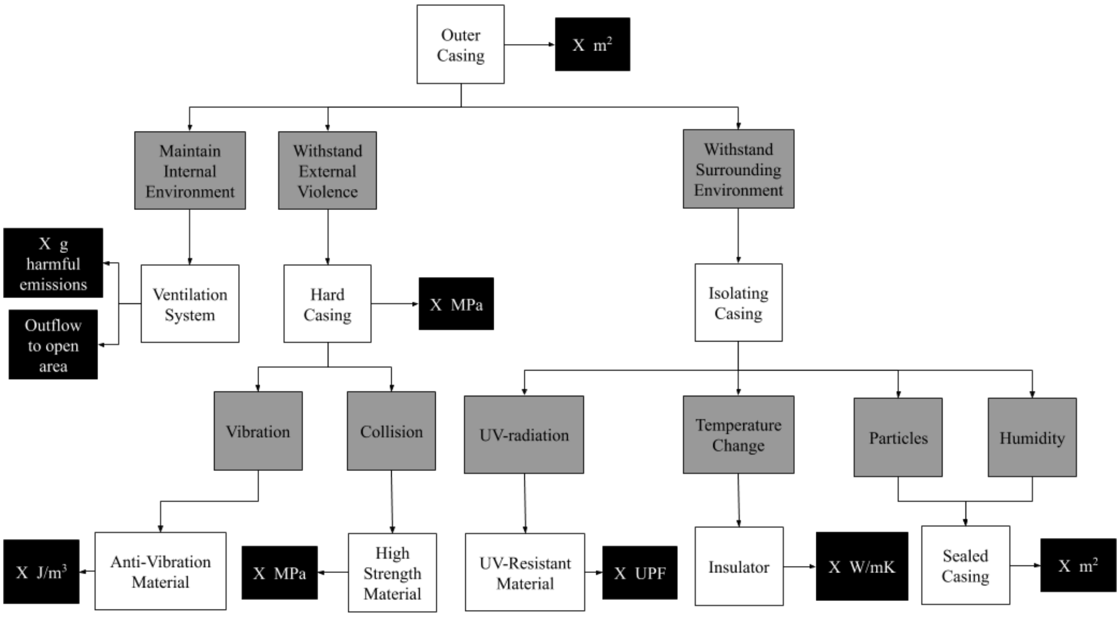

Figure 15: *Outer casing and its FRs and DSs*

The DS Inner Casing's FRs are to prevent energy leakage and withstand internal violence, see Figure 16. Energy leakage means that no electricity or heat is to escape the casing and hence, lower the safety for the battery. This means that the chosen material must have high insulation or a low conductivity (W/mK). The heat resistant material must be able to handle a certain temperature and the electricity resistant material a specific value for the resistance (Ω). Internal violence also relates to the safety of the battery but in this case, it is important for the casing to control the damage from the inside. The two possible abuses that might occur is either fire or chemistry leakage. The DS for chemistry leakage, absorbing material, connects to the constraint of being able to absorb a certain amount of chemistry (l/m^2) if a leakage would appear. This chemistry leakage involves both leakage of electrolyte from the cells and coolant from the thermal management system.

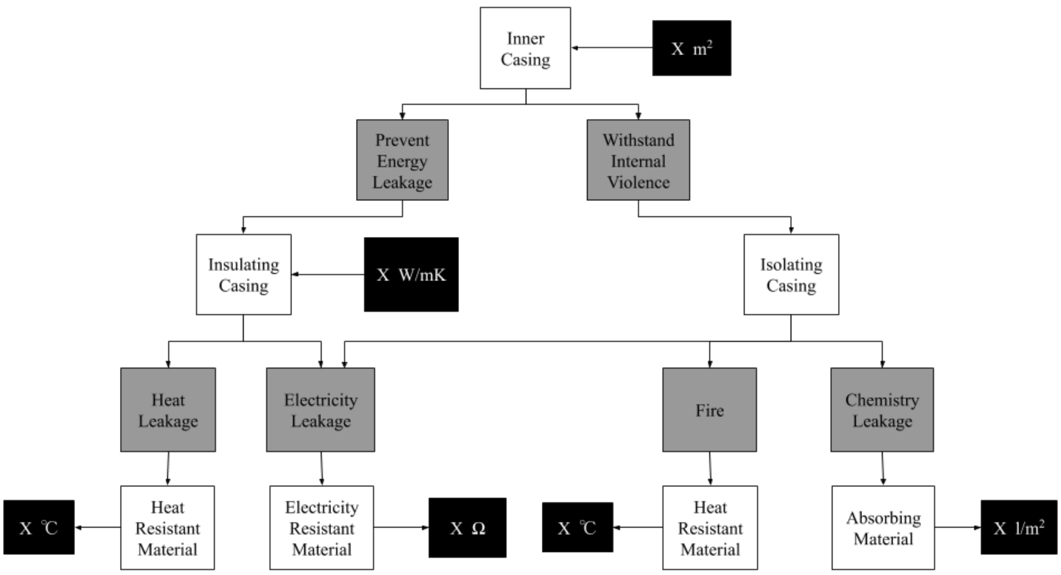

Figure 16: *Inner casing and its FRs and DSs*

As mentioned earlier, the system control is divided in hardware and software. Hardware contains six FRs, namely charge control, safety circuitry, sensor system, thermal management, communication and data acquisition, see Figure 17. Charge control involves carefully documenting the charge and discharge of the battery to make sure it is not overcharged, or the battery receives a too high voltage. Safety circuitry is the part of the Hardware that alarms when something is wrong, for example if the battery is overheated. The sensor system represents the physical measurements of the battery, it measures among other, the cell voltage and the temperature. The received values and information gathered are communication to the software included in the battery and can be done by either wires or wireless. Data acquisition (DAQ) is used to store and analyse values gathered from the battery and later build a database for system modelling. These mentioned FRs are not further investigated due to limitations mentioned in Section 1.4. The only FR that is further examined in hardware is thermal Management. Thermal management includes heating and cooling the battery to make sure it is within the right limits, hence the Cs for this is a range of degree Celsius (℃). The coolant used in the thermal system is either a liquid or air, where the liquid is constrained by a Volvo standard. Lastly, to receive a correct temperature in the battery, the coolant can either cool the modules or the cells directly with the help from a plate or tubes. These plates and tubes must be able to contain the right amount of liquid to transport heat to or away from the cells, resulting in the C being X litres coolant. The software's functions and solutions however are not presented here, since software is one of the stated limitations.

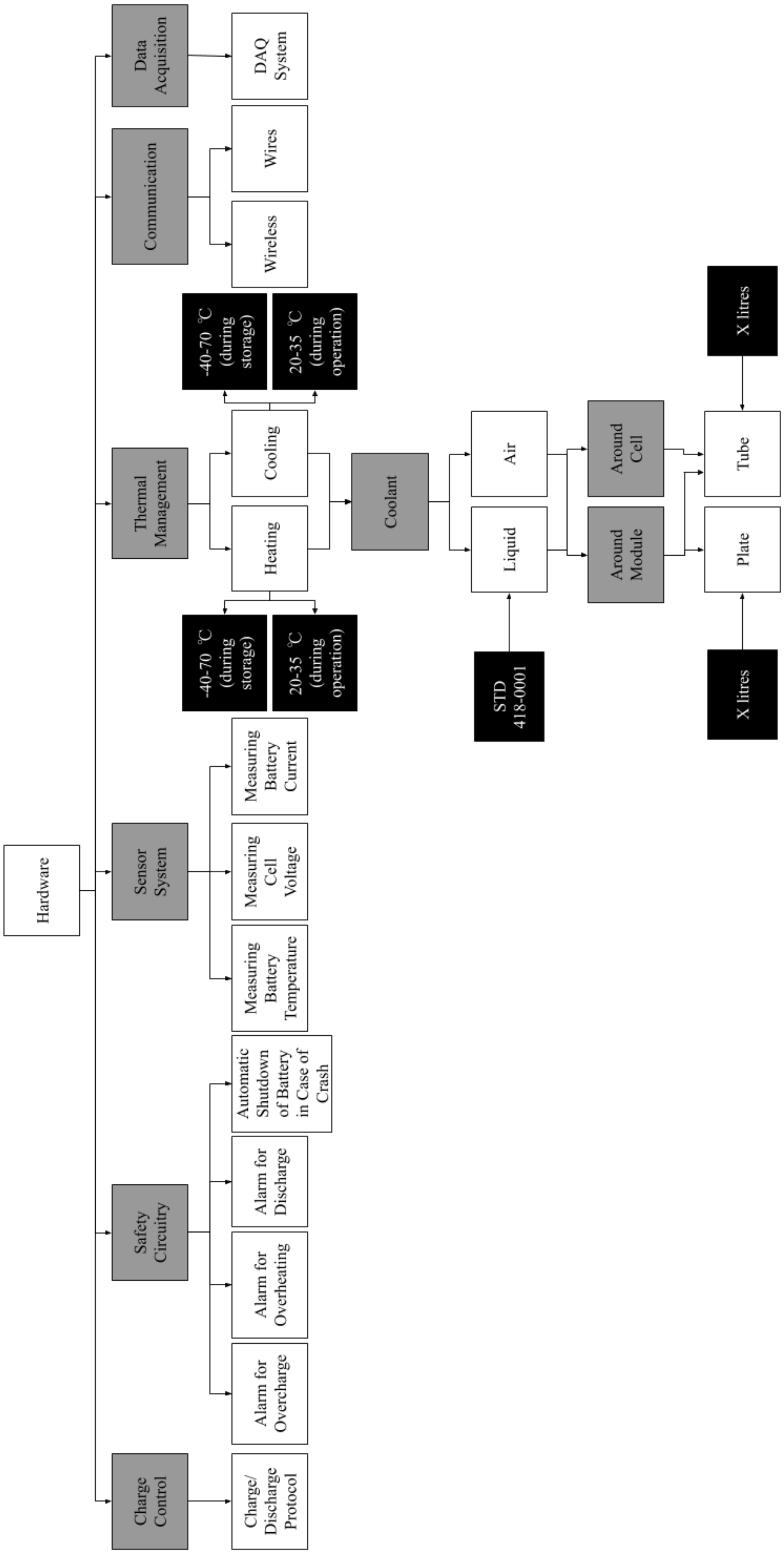

Figure 17: *Hardware and its FRs and DSs*

5

Benchmarking Results

Based on the functional modelling made in Chapter 4 benchmarking is performed to explore and gain knowledge of existing batteries. This information is important to reflect upon to understand how different functions are solved by different manufacturers.

5.1 Batteries

This section will introduce batteries used by various brands in the industry, mainly batteries from electric cars since this technology is more mature. A future battery is also presented since new batteries are always evolving and it is important to stay one step ahead as a competitor.

5.1.1 Tesla S 2014

Tesla S was the first sedan that Tesla designed from the ground up and it was released in 2012. The 2014 version of Tesla S has a capacity of 85 kWh (0.01 kWh/cell) and is an assembly of thousands of cells. The battery that power Tesla S Long Range, see

Figure 18, has a housing made from plastic (lid) and metal (bottom) and is placed on the bottom of the car. It is composed of 16 modules with 432 cells of the type 18650 and a NCA chemistry, resulting in a total of 6912 cells in each pack. (42) Furthermore, the cells inside the modules are packed in groups which are wired in series to each other, creating a battery inside the battery. The same goes for the modules which also are connected in series. (28) The small wire connected to each cell has two functions, namely being a link to the main bus and act as a fuse if the cell is damaged. Underneath the plastic housing of the battery but above the modules, Tesla has placed a fireproof cover that is assembled to the battery both with screws and adhesive. One BMU can be found on each module, all connected to the main BMU that is placed in front of the pack (situated in the rear edge of the pack in the figure below). The modules are placed in the pack with the help of a grid, see Appendix A.3, where they are secured to the bottom. (43)

Figure 18: *Tesla S battery pack* ***(42)***

The cooling system for the battery involves two cooling loops in each module with glycol as the coolant and each loop cooling half of the cells. By using two cooling tubes, Tesla managed to create a more efficient cooling system and therefore increase the safety of the cells. The loops are drawn inside the modules and around the cells, which is displayed in Figure 19. (44) To heat the battery during cold weather, Tesla reuses the heat from the drive motor and power electronics and consequently, a heat pump to help the battery stay in the right temperature range is not needed. (45)

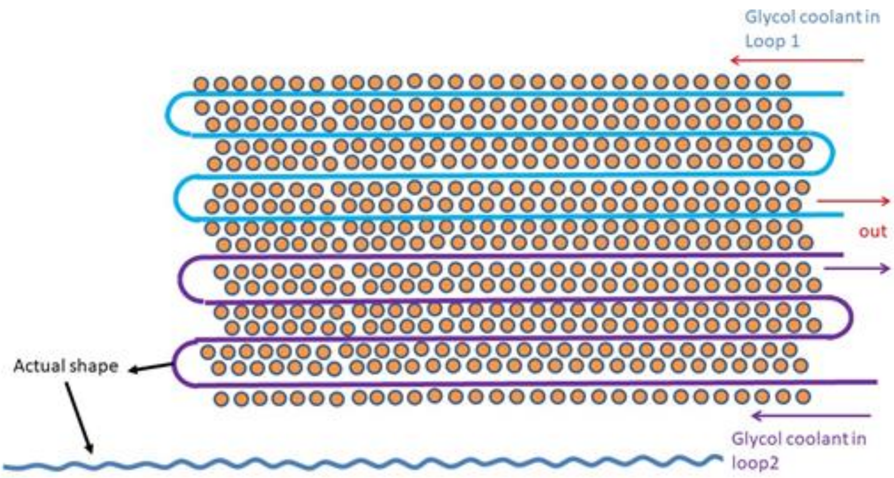

Figure 19: *The cooling system of the cells* ***(44)***

5.1.2 Tesla Model 3 Long Range

Model 3 is the third generation electric car that is released by Tesla. This car has a range of over 530 km in one charge, a capacity of 74 kWh (0.02 kWh/cell) and an energy density of 168 Wh/kg. (46) The battery used in this car is a complete upgrade from the battery used in Model S and instead of having 16 smaller modules connected to each other, it has four bigger ones. Inside these four modules are several so-called bricks that hold the cells. As seen in Figure 20, the battery consists of two smaller modules with 23 bricks and two bigger modules with 25 bricks, with each brick holding 46 cells leading to a total of 4416 cells included in the battery. Moreover, the cell used is the 2170 NCA cell, as Section 3.1.4 informs. (47) The inside of the modules can be described as a printed flexible circuit board with an insulated copper wire that is connected to each cell and next to this connection, a temperature sensor is attached to monitor the cells temperature. There is also a vibration pad on top of the modules, attached to the casing that reduce the vibrations from the outside reaching the modules and later the cells. (48)

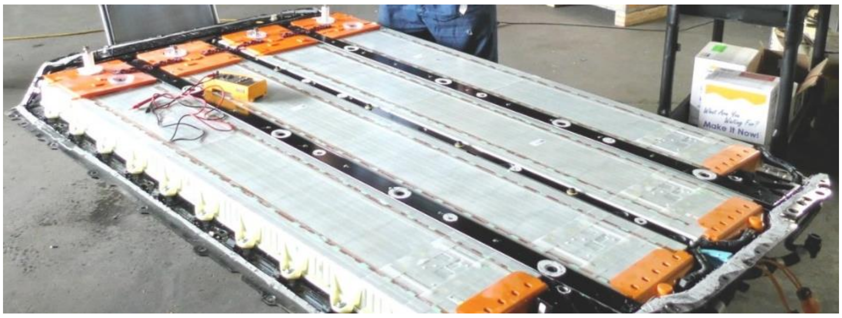

Figure 20: *The Model 3 battery* ***(48)***

The cooling system in Model 3 is an upgrade from the one in Model S. The new cooling system applies a manifold-based solution with the cells attached to the cooling tubes creating a more efficient cooling system for the battery, see Figure 21. The tubes cover a bigger area on the cells as well as do not have to cool the same number of cells as in Model S. This means that more coolant can pass through leading to more heat being transported away from the cells. Moreover, the cooling system is one solid part instead of being divided into several different tubes and consequently, the system is reduced in number of parts. (45)

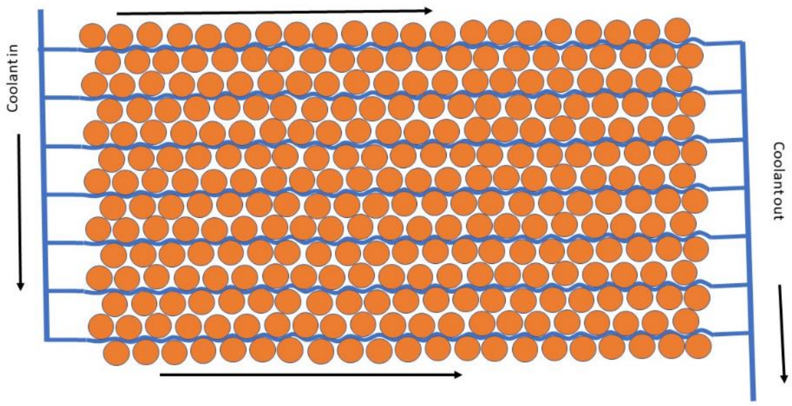

Figure 21: *The coolant flow in Model 3* ***(45)***

When looking at the BMS of the battery, each module has one circuit board and the modules are both connected to each other, the high voltage control board and the main BMS board. One major assignment that the BMS has is to control the temperature in each cell and the solution that Tesla has developed is that if a thermal runaway would occur, that specific cell will receive a current that burns up the connecting wire. Consequently, the cell is disconnected from the system and can no longer be used. (48) Tesla has designed their car so that heat waste from the powertrain can be used during movement as well as when standing still during for example supercharge. This is an important function since the battery's charge-rate drops if it is too cold. This also means that there is no external battery heater in the car and that Tesla relies on the software to control and adjust the temperature of the cells. All the main electric components included in the Model 3 battery can be seen in Appendix A.4. (47)

5.1.3 BMW i3 2015

BMW i3 is an electric car released by BMW in 2011, with the battery of the car placed under the floor (49). The battery as Figure 22a displays, has the weight of 230 kg, range of 160 km and the capacity 18.8 kWh (0.19 kWh/cell) (23). The housing holds eight modules, a BMS, a cooling system, a charger, a DC/DC-converter and a BMS salve. (38) The cooling system is liquefied with tubes covering the bottom of the pack as Figure 22b display, hence the modules stand on the tubes. The modules are connected to each other with a cord that is a plug-in on the positive side and permanently attached on the negative side. Moreover, the modules have a thick metal wall on two sides to optimize the protection during usage and a plastic cover on the top. The cells inside each module are linked to each other by a connecter that is laser-welded, and each module holds 12 prismatic Lithium-ion cells making the total number of cells in this battery to 96. The housing is made from metal with the lid having a gasket to protect the battery from the outside environment and to assemble the lid to the bottom as well as the vehicle, screws are used. (50)

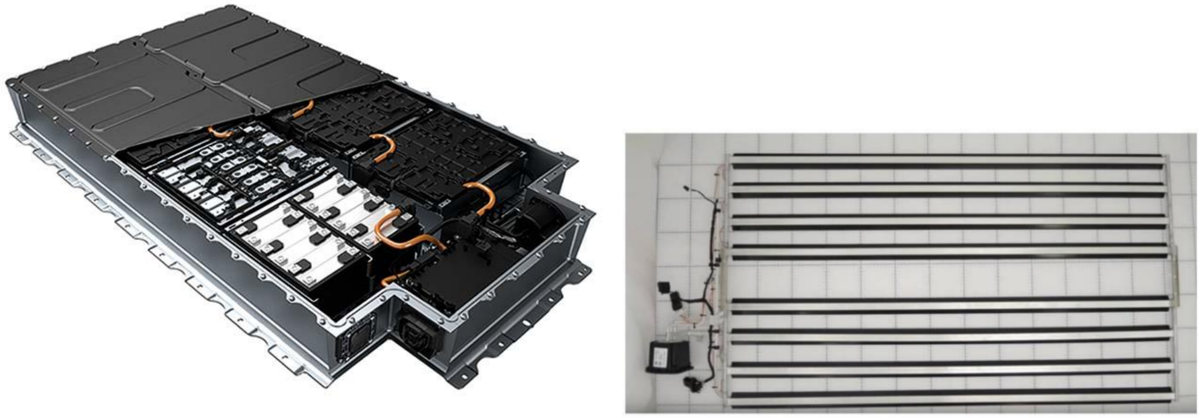

Figure 22: (a) *The battery pack of the BMW i3* ***(50)*** *and* ***(b)*** *BMW i3 battery cooling plate* ***(51)***

5.1.4 Nissan Leaf e+

Nissan Leaf was first introduced to the world in 2010 and Nissan is currently promoting the second generation, namely the Nissan Leaf e+. The battery, Figure 23, in this car has the capacity of 62 kWh (0.22 kWh/cell) and the range of up to 364 km. (52) The modules inside the battery consist of three different dimensions, 21 cells (left row), 12 cells (middle rows) and 27 cells (right row) and the number of modules with 21 cells and 27 cells included in the battery are four each meanwhile there are eight modules with 12. Concluding, the total amount of cells is 288 and are pouch-model lithium-ion cells (Section 3.1.4). (53) The thermal management system in this battery applies air as the cooling substance, where the air is channelled from the heating and ventilation system in the car and thereafter circulated in tubes around the cells. When it is cold weather outside, Nissan utilise a heat pump to warm the battery to the right temperature range. Finally, Nissan uses a gasket assembled on the housing, which is made from metal, to prevent particles and humidity to enter the battery pack between the lid and the bottom. (54)

Figure 23: *The Nissan Leaf e+ battery* ***(53)***

5.1.5 Chevrolet Bolt EV Battery

The Chevrolet Bolt EV battery is the second-generation battery pack created for Chevrolet Bolt, illustrated in Figure 24. It utilises 288 pouch cells with the chemistry NMC, resulting in a capacity of 57 kWh (0.19 kWh/cell) and a total weight of 435 kg. The battery packs housing is divided in two parts namely, upper- and lower casing where the lower part is made from steel and the upper part from fiberglass. In between the two parts, Chevrolet has added silicon as an isolation from particles and humidity. (55)

Figure 24: *The Chevrolet Bolt EV battery* ***(55)***

The BMS and power relays can be found inside the pack whereas the DC-DC converter, HV controller and other HV units are mounted in other parts of the vehicle. Furthermore, the pack consist of ten modules, divided in two rows and two levels with the lower modules containing 30 cells and the upper modules 24. The cells in this battery are packed together, more specifically three in parallel with a metal enclosure held together with long bolts.

The thermal management includes thermistors attached at the end of the module that senses the temperature of the cells and regulates it after what is needed, and horizontal cooling plates with channels for liquefied coolant which the modules are stacked on. Finally, metal sheets in between the cell packages helps with transporting the heat from the cells to the base. Each layer has its own cooling system with hoses to the coolant loop and a lower cooling plate base.

5.1.6 LION Light Battery

The LION Light battery is a concept battery created by LION Smart GmbH that is currently being installed and tested in the BMW i3. It is designed to have a high energy density, longevity and robust safety concepts. Other criteria's that are considered are the cost of assembly and material, and the developed LION Light battery is modular with the housing coming in different sizes depending on how much capacity is needed, and the smallest battery being shown in Figure 25. This has 8 modules and a capacity of 101 kWh (0.01 kWh/cell) meanwhile the biggest battery in this product family has a capacity of 203 kWh and total of 16 modules. (56)

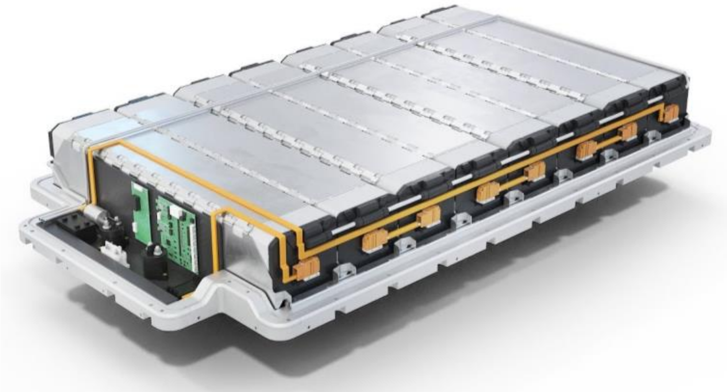

Figure 25: *The LION Light battery pack showcasing the modules* ***(56)***

One module consists of 12 so called Supercells, a Supercell is small module holding 84 cells in a housing connected to each other in parallel. The cells are of the type 18650 but can be adapted to other cell-types as well. To monitor the temperature and voltage of the cells, the Supercell features a measurement card on top that is wireless and cascaded in a master-slave arrangement, with the possibility to transmit the signals via an infrared interface. The Supercell, measurement card and cells are showcased in Figure 26. (56)

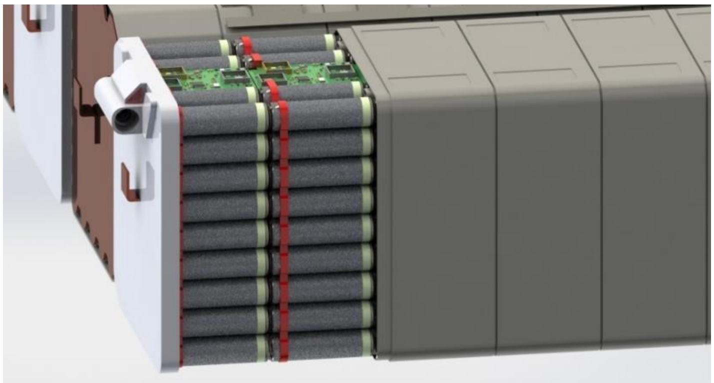

Figure 26: *The LION Light battery Supercell with cylinder cells and measurement card* ***(56)***

By implementing a wireless communication system, the risk for cables to be put under mechanical stress, corrode or be affected by electromagnetic radiation is minimized. Furthermore, the assembly of the battery is improved since there is for example no complex attachment of cables and joining processes, and as a result having the potential of being highly automated.

The thermal management system applies a dielectric fluid as the cooling liquid. (56) A dielectric liquid is the liquid state of a dielectric material, for example purified water or transformer oil, and it has high thermal stability, is non-flammable as well as has good heat transfer properties and a low cost. (57)

The thermal management system is in direct contact with the cells contributing to an effective heat transfer and a uniform temperature in all the cells. If a thermal runaway would appear in one cell, then that cell is disconnected from the system by a fuse and even though one cell is lost, the rest of the system is still functioning. (56)

6
Modularisation Enablers

This chapter captures the final results from the project, describing the findings applied in functional models and assessed from a DFA and DFD point of view. The components of the "ideal battery" concept are also presented.

6.1 EF-M Models of Benchmarked Batteries

When comparing the different batteries mentioned in Chapter 5 to the created EF-M models in Chapter 4, it is discovered that a great deal of information is missing due to confidentiality, especially when it comes to other brands than Volvo. The batteries used by Volvo are currently manufactured by external companies and therefore also have limited information to some extent. The knowledge gathered from the benchmarking is summarised in a table in Appendix A.8.1, describing how the different batteries solve the outlined functions. What can be interpreted from this summary is that the majority of the batteries uses a housing constructed by metal and if cylindrical cells are applied, the thermal system focuses its cooling directly onto the cells. On the contrary, pouch- and prismatic cells, have the cooling located at the modules. All the batteries' housings are sealed with screws and the housing's design together with the material, solves most of the outer casing's FRs as shown in Figure 27, including; UV-radiation, vibrations and collision. To protect the inside of the battery from particles and humidity coming from the outside, either a gasket, adhesive or silicon is applied by the different brands. Electricity leakage is solved by adding an insulating material around the wires that conduct the electricity from one place to another, and the surrounding parts, as contactors, are also created from an insulating material to maximize the protection.

According to Ashby et al., the different material groups that exist are natural materials, composites, ceramics, polymers and elastomers, glasses and metals and these can thus be used for the different DSs. Figure 27 represents the materials that can be applied for the Outer Casing's DSs. Here, vibrations needs to be minimized to avoid permanent damage and therefore, the chosen material must have the ability to absorb these movements. Material that have the capability to do this are natural materials, ceramics, composites, polymers and elastomers. Metals and glass have a high Young's modulus and are consequently too stiff to use as a solution to this problem. On the other hand, metals as well as composites, polymers and elastomers are good solutions for collision due to the amount of load these materials can withstand, see the material property chart in Appendix A.8.2. Moreover, these materials can handle temperature changes without losing the material properties that is of advantage, as Appendix A.8.3 show. Next, materials that do not weaken from UV-rays are glass, metals, polymers and elastomers and are thus possible solutions for withstanding UV-radiation. Particles and humidity must be isolated from the inside of the battery hence, the material that is applied must have the ability to completely seal the battery. For that reason, ceramics, composites or polymers and elastomers are beneficial to utilise. (58)

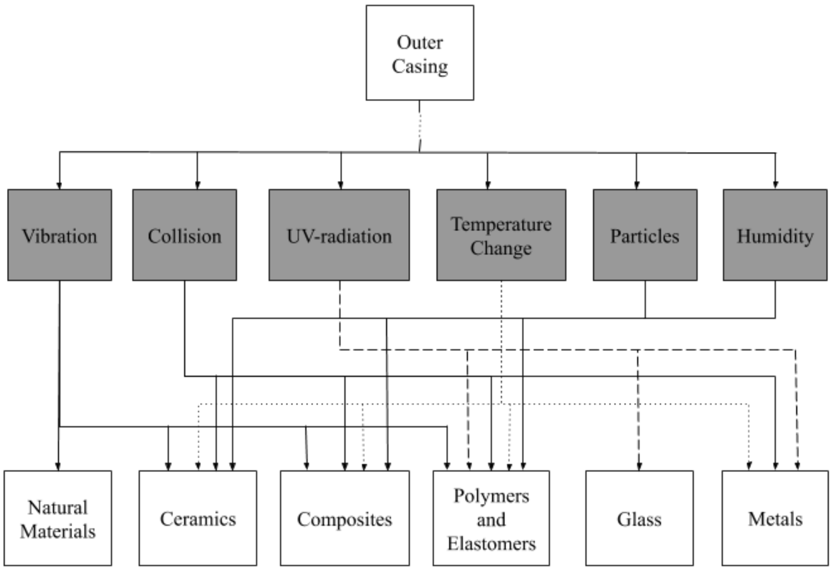

Figure 27: *Materials that can be used as solutions for the Outer casing*

Figure 28 presents the possible materials for the Inner Casing (a) and Hardware (b). Heat- and electricity leakage both demand a material that is insulating so that neither type of energy is moving around freely. Consequently, the preferred materials for these two are natural materials, ceramics, composites, glass or polymers and elastomers, as Appendix A.8.4 indicates. Although, the material must be able to handle high temperatures which leads to natural materials being removed. Further, fire requires a material that can handle high temperatures without deforming, hence metal, glass, polymers and elastomers and some ceramics are possible solutions. However, glass is not an optimal material to use for this case due to its brittleness and while exposed to high temperatures, glass shatters. Materials that do not have the property to handle the function chemistry leakage are natural materials, which makes the other material groups mentioned in Figure 28a possible solutions. The chemistry that is leaked, for example coolant or gas, must either be absorbed or ventilated, which makes polymer a good option. The ventilation tubes can be made from either of the four material groups but since a low weight is required, metals, glass, ceramics and composites are removed. (58)

Lastly, the material solutions displayed in Figure 28b for hardware includes metals, glass, ceramics, composites, polymers and elastomers. Either one of these are possible solutions for thermal management around module or cell. As mentioned earlier, glass is a too brittle and according to Appendix A.8.5, it has a too high density and is therefore removed. Metal on the other hand, is the preferred option when the thermal management is located around the modules, see Chapter 5. It works well with both managing the coolant and enabling conductivity. When the thermal management is around the cells, the polymers and elastomers are chosen due to their density and plasticity. The area close to the cells are often more complicated than the area around the modules and on that account, the needed shapes are complex, and the chosen material must be easy to form to fit this shape. (58)

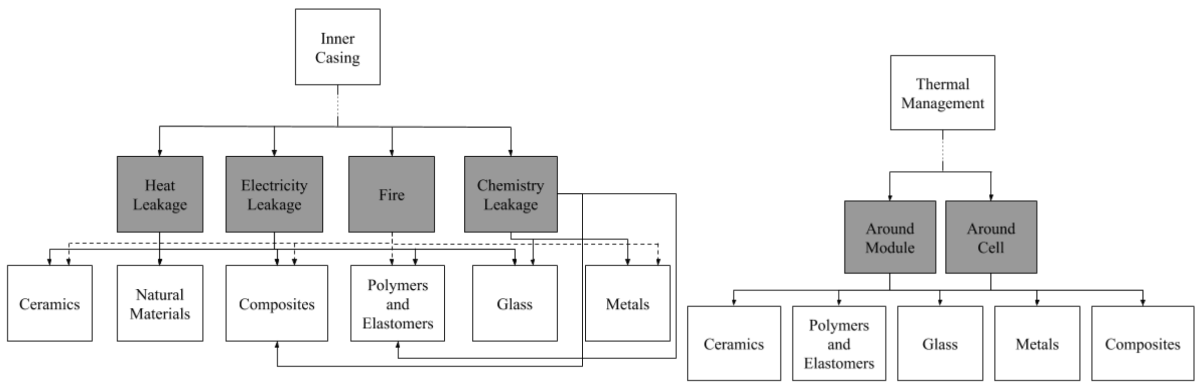

Figure 28: ***(a)*** *Materials that can be used as solutions for Inner Casing and* ***(b)*** *Thermal Management*

6.2 DFA and DFD of Benchmarked Batteries

DFA and DFD contribute to reduction of complexity, time and therefore costs. Once the production of batteries has increased, automated disassembly can be introduced in the future. For this to be possible, it is important to consider the design of the battery and to make sure it has a minimized amount of materials and parts, in addition to suitable joining techniques.

When examining the batteries mentioned in Chapter 5 from a DFA and DFD point of view, some are better than others. All battery housings are assembled using screws which is beneficial for the disassembly since it is possible to remove the lid without damaging it. However, a large amount of screws is needed, making it a time-consuming activity and an increased number of parts results in longer lead times as well as higher material usage. Another thing the batteries have in common is the usage of modules. BMW i3's solution for how to connect the modules to each other is beneficial both for DFA and DFD since the contactor between the modules is a plug-in, which is both easy to attach as well as remove, resulting in a faster process. Another good example of module assembly and disassembly is found in Tesla S which also has modules mounted to the pack with four screws. To access these screws a plastic cover must be removed, but once that is gone, it is easy to unscrew the modules and later on lift them. Also, the electrical connection between the modules are difficult to disconnect due to many connecting points.

Two kind of cooling systems are used by the different batteries, either cooling around the modules or the cells. The ones that have cooling around the cells, such as Tesla and LION Light, have trouble with disassembling the cooling system. In Tesla's case, the cells are glued to the cooling system which means that the cells cannot be removed without damaging the cell or the cooling system itself. On the contrary, Chevrolet Bolt and BMW i3 utilise a plate that the modules stand on, resulting in the plate being exposed when the modules are detached. Due to the thermal system being its own component, it is possible to both add and remove it without making any damage, giving that the module mounting or removal is done correctly. All cells in the stated batteries are connected in series by being welded to wires, meaning that the cells are not easy to remove and consequently, they are optimized for assembly but not for disassembly. Finally, Chevrolet Bolt and Tesla S have different materials for the lid and the bottom of the housing which can cause problems for disassembly, when considering recycling options. It is for that reason beneficial to use as few dissimilar materials as possible.

6.3 The Ideal Battery from an Assembly and Disassembly Perspective

As mentioned in Section 2.1.3, modular products are of great value both for the customer and the company. A battery has several ways to implement modularisation and among these are design of the housing and module as well as concerning the management of its environment. By using a design that is applicable to all the trucks included in the Volvo, the battery can be utilised between the different brands without the need for adaption, predicting that the space dedicated to the battery is the same. On the other hand, the design can also be modularised depending on the capacity, performance and brand-uniqueness demanded.

6.3.1 Battery Housing

The battery pack has a rectangular shape where its length can be modified, depending on the capacity needed. The battery housing will be modularised in a way that three lengths of plate exists, to create a larger space for packs needing additional modules. By using this type of profile, the contact surface to the beam will be larger than a cubic form and the beam can carry more of the battery's load and moreover, it is easier to modularise and maximize the space than if a cylindrical form would be utilised. With the aim of reducing the amount of packs per truck by adjusting the size instead of adding extra packs, it contributes to less objects to lift, less supporting structures and screws to attach and hence, a faster assembly process. This is accomplished by the modularised pack-size where the increasing size, shown in Figure 29 and Figure 30, can be connected to the corresponding duty truck, e.g. the smallest pack can be fixated at the light-duty truck. The different packs are produced from plates made of the same metal and is divided in the bottom casing, including the base and the sides, and the top casing, the lid. The plates are joined together with welding and the pack's top and bottom is assembled mechanically using nut and bolts with the same head variants, and from the same direction to prevent change of tool and location during manufacturing. This is chosen because of its high joining strength and simplification of the disassembly at any service centre. On the other hand, by joining several plates together that are being subject to external loads, especially the bottom plates, will have a large impact on the fastening points and decrease the endurance. Despite this, the packs today are assembled in a similar way, using several plates working as the housing and it is usually the chemistry in the cells, the SOC capacity, which fails at first.

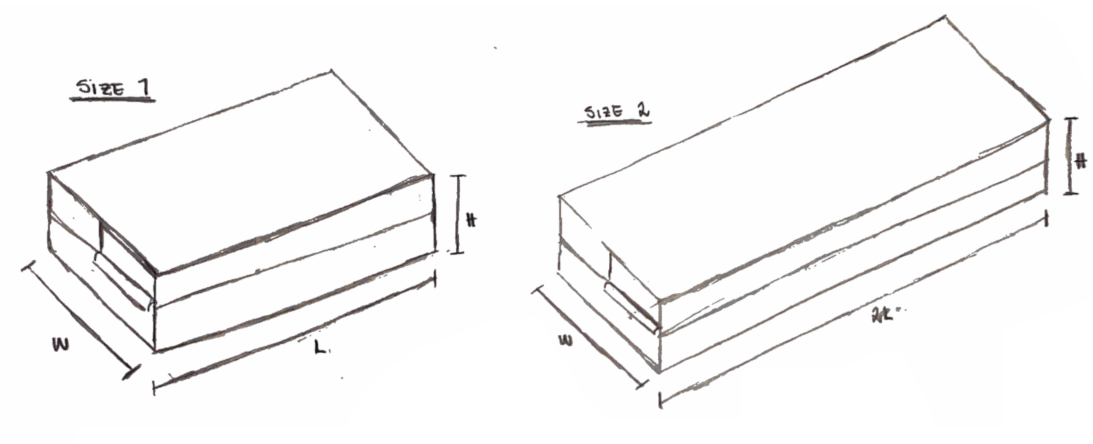

Figure 29: *Two possible sizes for the pack with two layers*

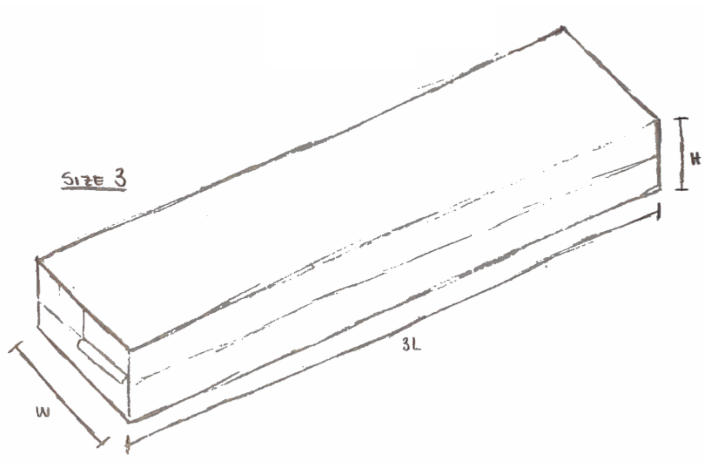

Figure 30: *Third potential size for pack with two layers*

The lifting points are placed at the bottom of the battery instead of on the top as seen in many of the current batteries that requires a special lifting device. In fact, for optimal place- and displacement of the battery pack onto the truck's beams, a lifting truck should be used. To lift the battery from underneath, it requires a stable and strong housing to prevent the battery from deforming because of its own weight. At the production, plates should be attached to the beams to enhance the support from the truck.

The optimum way to isolate the pack is performed utilising gaskets made of polymers, situated at the corners of the pack and close to where the top- and bottom casing is joined together, see Figure 31. Due to the different sizes of packs, the needed isolation varies. In the larger pack-size, there are more possibilities that leakage would occur, and an enhanced isolation is applied. Conclusively, the aim is to apply the same type of joining method and material throughout the housing.

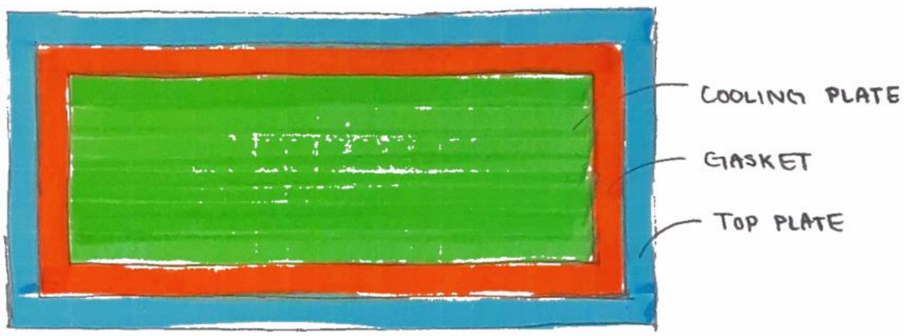

Figure 31: *Overview of the inside of the top plate*

6.3.2 Battery Module

The same modules as used by Volvo today will be applied for the purpose of promoting mass-production, more specifically containing prismatic cells. These cells have high capacity, good lifetime, high packaging density, are easy to stack and are appropriate for the rectangular shape of the pack for space optimisation, see more in Section 3.1.1. The modules can thus be connected in parallel and in series, making a modular design feasible. Moreover, the modules will have the same size instead of using different ones as in LION Light since prismatic cells already fully utilise the space. It would be preferable to make the pack as compact as possible, making transportation easier and safer in addition to reducing the weight, preventing deformation and fatigue regarding both the pack and the truck beams. In the progress of making the design smaller, the target is to decrease the width of the pack and instead increase the height, by adding layers of modules and as a result, provide a better distribution of the loads since a larger area is joined to the beams. The modules' size will be as small as possible for easy dismantling, as long as the required capacity is reached. At the moment, the pack will have two layers but as cell technology evolves and possibly make a more compact design available, so can be the case for the pack solution.

6.3.3 Module Frame

It would be preferable to not fixate the modules to the housing but rather let them be "loose", as in existing solutions for attaching AA batteries. This is done by adding and fastening a frame to the bottom of the pack, as illustrated in Figure 32, with the structure shaped after modules aligned including positive (spring) and negative (plate) terminals for each module to be clicked in. By being able to "click in" and "click out" the modules, this will facilitate the dismantling of modules that are damaged and in need of service for a reuse purpose or to be recycled. The module itself is easier to lift, handle and transport since it is safer, small and weighs around 10-20 kg. Additionally, several module frames can be connected to each other to fit the length of the battery housing. Also, in the case of using two or more layers of modules on top of each other, a middle plate is placed between the modules on the lower layer and the module frame above, see Figure 33. Only the top layer of each battery will include a Battery Management box except for the modules.

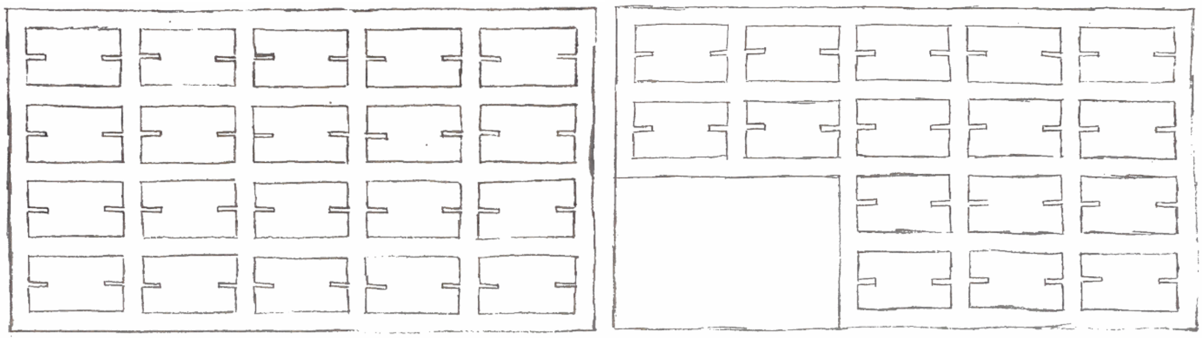

Figure 32: *(a) Module frame and (b) Module frame with place for the Battery Management Box*

A battery contains many wires that connects both the cells, modules and software to each other. To make sure that these wires are placed tidily in the casing and keep them from moving around in the pack, cable clips will be used. Here, the cable clips are included in the module frame for a clean look and a secure environment. These are therefore pre-mounted to the frame, creating an easy assembly. The frame and cable clips enable guidance to where the wires are to be attached during assembly and where to find them during disassembly. This will provide easy accessibility of the wires but also the modules, which is why the frame is placed on the bottom and nothing is in the way once the top casing is removed.

Since the battery pack is subject to repeatedly applied loads, an important design solution is to impede these vibrations, preferably close to the electrical connections. Consequently, by attaching vibration pads under the module frame and on the sides of the housing as Figure 33 indicates, i.e. on the bottom of the casing to make sure the sensitive electrical wires are in contact with it. Additionally, it is important that the vibration pad is made from an insulating material to assure it is not turned into a conducting plate.

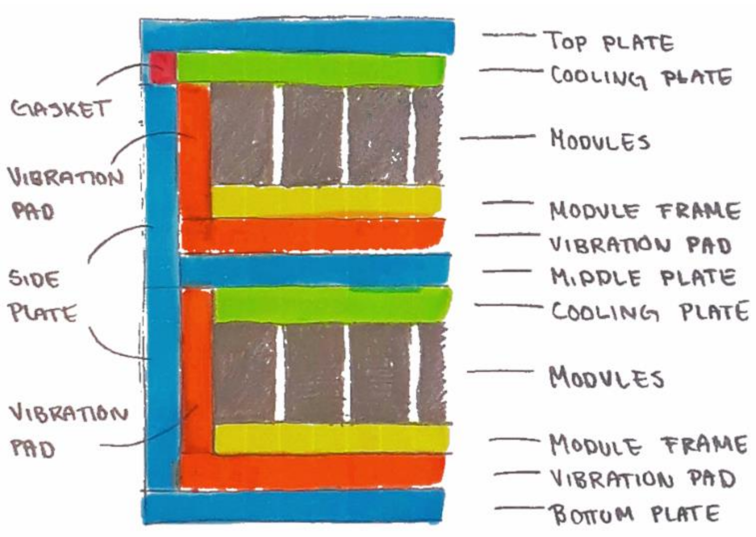

Figure 33: *The different layers of the battery*

It is also crucial to make sure all the parts that are conducting electricity are covered to minimize the risk for an operator to get in contact with them. These covers should be made from an insulating material and could for example be caps on the connectors on the connection points. Even though safety of the operators is highly important, it is also essential to reach the fastening points with tools for both assembly and disassembly. With tools, it is possible to reach narrow spaces that are not possible to reach with hands and therefore, these areas are covered with insulating material such as the caps mentioned before. The tools used for mounting are preferable made from for example a polymer or if created from metal, covered with a polymer to decrease the risk of injuries since there is a high risk when handling HV batteries as described in Section 3.1.6. Additionally, the top layer inside the pack can be removed for easy access to the layer underneath. Hence, if a part breaks in the lowest layer, it is easy to reach and replace the broken part. Removable layers also enable adaption of the capacity to the vehicle, since capacity relates to the number of layers connected in parallel.

6.3.4 Battery Management Box

A box that is easy to access and remove will be used, including all the components that controls the battery. It is placed on the edge on the short-side (close to the beam and the cab) for space optimization, easy connection to the truck and protection of those cables from the surrounding environment. It should be located on the top of the pack, to minimise the risk of abuse from objects on the road. By using the box, the modules are simpler to reach compared to earlier batteries where for instance, the BMU had to be removed first. In addition, to facilitate disassembly both regarding removal of the box but also of the modules, the communication should be made wireless and thus, adding a receptor to the box. The components in the box are mechanically attached, using the one screw variant, to easily remove and replace them as well.

It would be of interest to have a standardized contact for the pack to simplify the charging process, making it possible to charge and discharge wherever and whenever, providing safer and faster handling of the battery. The contacts inside the battery, the ones connecting the modules to each other as well as the internal HV- and LV connectors are preferably plug-in contacts. By utilising plug-in contacts, it is easy to both attach and remove them when needed and the time for assembly and disassembly is shortened. In addition, the contactors inside the box need to be exchangeable and assembled with one variant of screws. These are frequently torn down because of the formation of sparks, high voltage and numerous driving cycles, turning the engine on and off.

6.3.5 Thermal Management

A cooling plate is placed on the lid of the pack with the modules and module frame underneath it and is therefore separated from the electrical module connections. There is also a cooling plate placed on the middle plate between the layers, to cool the modules in the layers below. By keeping it as one part it is possible to both add and remove it as well as exchange it without being dependent on another part. The size of the cooling plate is adapted to the different sizes the pack is available as hence, in three dimensions. Additionally, the inlet and outlet for the coolant are placed on the opposite side from the battery management box and the reason for this is to keep the electronics and the coolant separated in case abuse happens, see Figure 34. The surrounding sub-assemblies can then also be removed without interfering with any part of the thermal system, leading to easy service and disassembly of the battery.

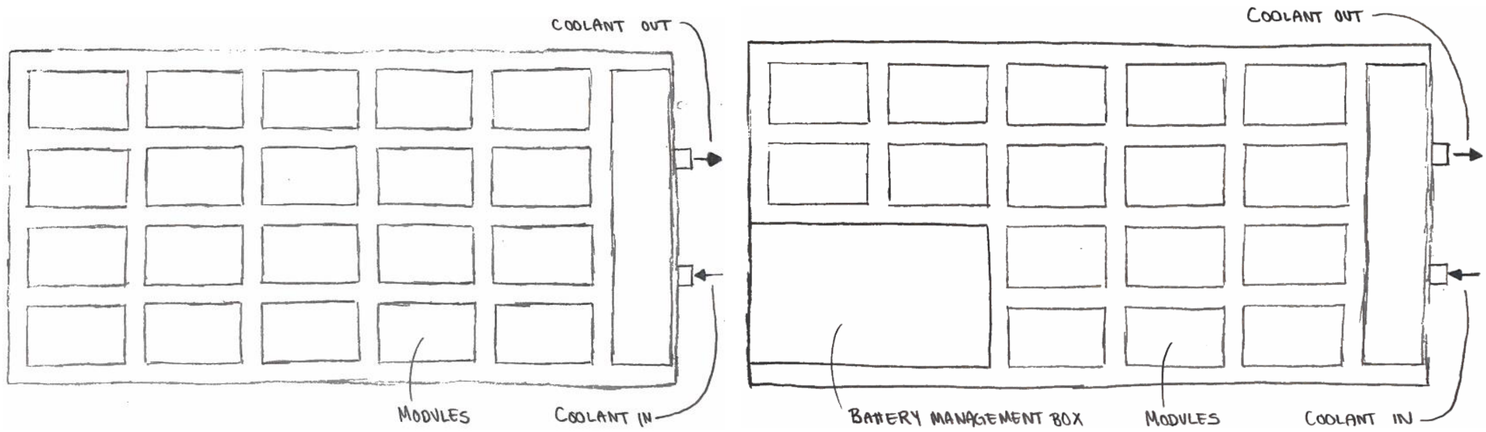

Figure 34: *Overview of the inlet and outlet for the coolant*

7
Discussion

The discussion comprises various tradeoffs that are necessary to make when designing a battery pack, in addition to a commercial assessment of batteries and recommendations to Volvo regarding future investments and research.

7.1 Design Tradeoffs

When designing a battery pack, it is important to weigh different parameters against each other to acheive a suitable design. It is therefore significant for these tradeoffs to have a valid foundation to stand on. One tradeoff that needs to be accounted for is comparing safety of the battery against its weight. The goal when developing a vehicle is to keep it as light as possible to ensure low consumption of energy and enable more load to be applied, meaning that the battery's weight must be as low as possible and at the same time be safe to use. For instance, the battery could be covered with tungsten alloys to secure it during both internal and external abuse but this results in a heavy product, see Appendix A.8.5 for comparison of strength versus density. Consequently, the battery is covered by a material with high strength but also with high density. Therefore, steel is chosen for the housing in this case due to its properties connected to strength. Steel is possible to form into the desired shape with the desired thickness, and still have the preferred safety properties preserved. It is not the lightest material but since safety is such an important part of the battery, the protection properties weighs more than it being made from a lower density material.

Safety is also a tradeoff when comparing it to accessability. It is important to be able to reach all parts but at the same time it needs to be secured, making this tradeoff especially substantial regarding DFD due to it being a concern when the battery is disassembled. A battery is taken apart for several reasons, as service or recycling, and during these actions it is significant for the battery to be safe to work with since high voltage is involved. At the same time as a safe interaction is necessary, the operator is required to access different parts to be able to move them. The operator is therefore demanded to wear safetygear and the battery must be covered with materials that remove the conductivity. The safetygear is clumsy and consequently, it is difficult for the operator to both access parts that are located in small areas as well as grasp them (28). This results in a complicated disassembly but a safe environment, where specifically produced tools for the dismantling might be a favourable solution. Further, safety also concern accessability in case of internal abuses, in the way that the pack should be easy to enter if a thermal event occurs either by simple dismantling or by the ability to attach a component to the pack, as a hose.

Additionally, DFA and DFD is a tradeoff that is becoming more and more important due to the increased interest in remanufacturing and recycling. What is seen as easy assembly is commonly something that complicates disassembly, for example permanent attachments as welding the cells to the wires or the top- and bottom housing together, are not recommeneded from a disassembly point of view. For remanufacturing in particular and for promotion of an environmentally friendly design, easy exchange of damaged parts and aged cells is of value to prolong the battery's life. Despite this, aspects as how the cells are affected during assembly needs to be reflected upon as well when selecting the joining method. There is a risk that the cells get subject to vibrations that can harm them which is essential to prevent and might be more of substance than the disassembly perspective.

Finally, it is crucial to find the right balance between designs for easy disassembly as opposed to design for difficult disassembly. By facilitating the procedure, it would contribute to enhanced efficiency, reduced cost and time at the remanufacturing workshop. On the other hand, an advanced joining of the battery pack could prevent competitors from accessing it and therefore, secure confidentiality.

7.2 Ideal Battery Design Assessment

The Battery Housing is designed to be placed at the same position as the current Volvo batteries are today. If the placement of batteries would change, the design might need to be changed to fit the new design of the chassis. Although, the rectangular shape is recommended to keep due to its increased contact surface with the beam. On the other hand, a solution that distributes the weight of the battery over the beam is more ideal due to it receiving support directly from the beams and not having to fixate extra plates to the beam for support enhancement. On the other hand, a solution where the battery is placed over the beams could lead to a more difficult disassembly since it is then harder to reach than when it is placed on the sides of the beams. Also, the Battery Housing is the component that protects the inside of the battery from external abuse, for example from objects on the road or collision. Consequently, it is important to reflect on how increasing the length of the battery also results in a bigger area for objects to hit. Additionally, by adding more layers of modules and hence increasing the number of cells, it contributes to an increase in capacity and in distance the truck can drive but it also means that more energy is gathered, a potential hazard if handled incorrectly or being exposed to either internal or external abuse. However, a bigger battery with higher capacity decreases the total amount of batteries needed on a vehicle and hence, the weight is reduced. At the moment, the Battery Management Box is located on the inside of the Battery Housing closest the beam with no space around it, requiring disassembly of the battery from the truck to enable movement of the box.

The Module Frame design is based on the current solution for regular batteries in for example remote controls, where the batteries are smaller than the intended modules in this design. Smaller batteries are easier to fixate since the demanded pressure on the positive- and negative poles is lower than a module requires.. Even though using a frame is advantageous in an assembly and disassembly perspective, it is important that the modules are attached properly during usage to make sure the movements are eliminated, and internal damage is avoided. If the modules would move around, the energy supply to the vehicle is disabled and the modules could potentially collide and get damaged. Moreover, by using the “click on, click off” solution for high voltage batteries might contribute to faster wear out on the connections and a decreased isolation. This could be problematic if the connections need to be replaced before the modules, leading to unnecessary service time.

Thermal Management is an important element in a battery and by keeping it separated from the Module Frame and Battery Management Box that holds the electronics, the risk for the coolant to get in contact with the electricity is minimised. Although, if coolant would leak from the plate, it would drip down on the modules and then on the wires, located on the frame, before congregating on the bottom. Therefore, it would be better for the plate to be on the bottom of the pack but on the other hand, a coolant leakage is more likely to happen in the connection points for the tubes rather than from the plate itself. It is therefore important to ensure that the connection between coolant inlet and outlet and the plate are tight with no probability of leakages. If the plate would be placed on the top of the modules, it is easier to reach, repair and disassemble the plate as well as the connection points. Furthermore, by placing the cooling plate on the lid it requires accurate measurements during assembly to ensure that the plate and modules are in contact. If not, the efficiency of the thermal management is decreased, requiring more coolant to circulate.

8
Conclusion

The report encompasses information and knowledge regarding battery packs used for electric vehicles both in Volvo but also in other trademarks with data from public sources. Investigation on the current battery solutions for trucks, busses and cars that exists on the market were made, determining how the chosen brands solves different functions. The gained knowledge is stored in enhanced function-means models and further assessed concerning its compatibility with DFA and DFD characteristics for the intention of developing *“the ideal battery”*. The important battery pack interface properties, from an assembly and disassembly perspective, on the housing are that the same material (steel) and joining method (mechanical fastening) is used on all available sizes. The box has a modularised length that is doubled or tripled if more capacity is desired. The battery modules on the other hand, are already modularised in the way that the same type is used throughout the pack. Next, the module frame consists of one frame with equally distributed gaps for the battery module connections. Two respectively three of these frames, modules, can be applied in the heavier trucks. The battery management box is its own module for the reason that it is separated from the battery modules and the same box content can be used regardless which truck. It is attached mechanically with one screw variant as well as using one standardized charge contact to facilitate service of the pack. Finally, the thermal management is solved by the use of a cooling plate that is modularised similarly to the battery housing with three different plate sizes, which are fixated on the lid and not attached to the rest of the battery pack content. On the subject of essential design tradeoffs, it was discovered that a great deal is made regarding safety. These include for instance, safety against weight or accessability, where safety is considered as the more significant characteristic and is non-negotiable. Also, design for assembly and disassembly might be contradictory as a fast and easy assembly can contribute to difficulties in remanufacturing and recycling and consequently, a shift in focus to simplify the disassembly process is necessary in the design for second life batteries.

Furthermore, even though common modular architecture was not used in this study, it is seen as a valuable method for Volvo to apply in future development processes, especially for future battery production. Batteries are seen as both common modules and flexible modules due to the possibilites to be chared between the same models as well as between different sizes of vehicles. They are not brand modules because of them not having a specific design for a particular brand. By applying common modular architecture, a foundation of platforms that utlises the same kind of interfaces for batteries can be built, resulting in transferable solutions between plants. Although, for a method such as CMA to function properly, it is important to have well functioning chanels of information and documents where long lead times to access the necessary material is decreased.

The technology of lithium-ion batteries is still being subject to changes and updates contributing to difficulties in predicting the future. New technology also imply that all products must be updated and hence, involving all actors in the product life cycle. It is for that reason crucial to track these ongoing improvements of technologies to stay competitive in the industry. (59)

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Appendix

A.1 GANTT-Chart

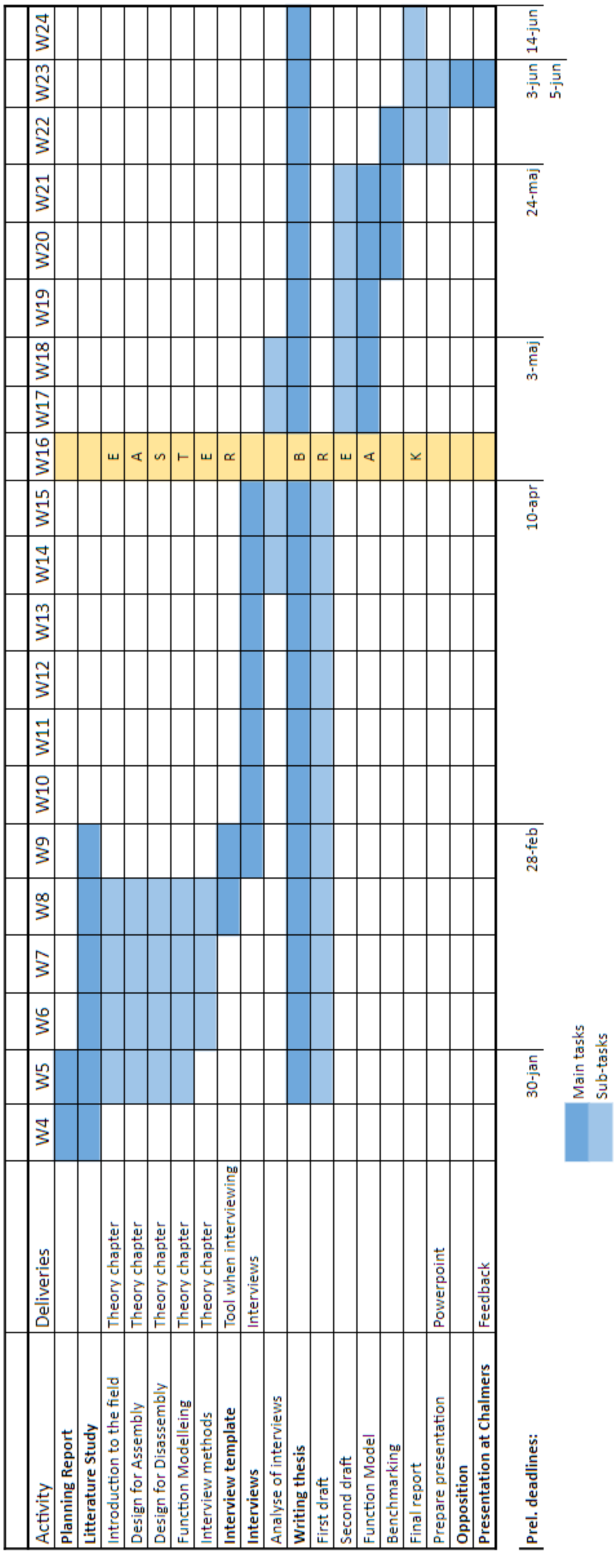


Figure 35: The GANTT-chart for the project

A.2 The Different Cells' Electrolyte

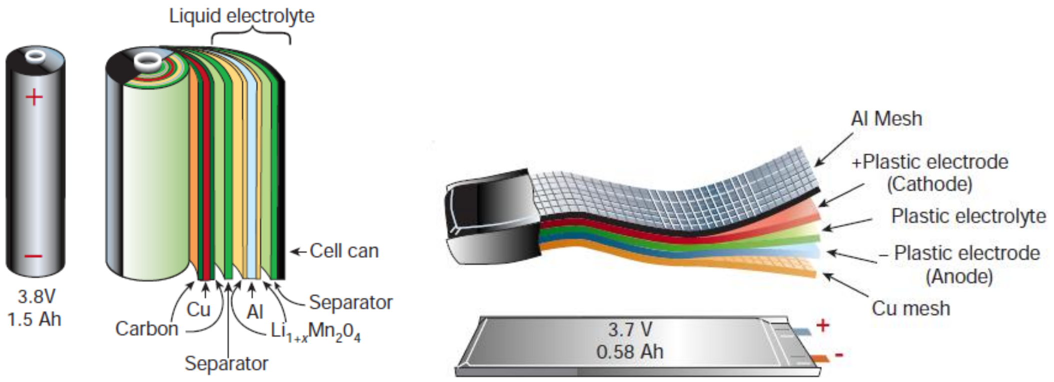


Figure 36: *The electrolyte in a cylinder cell (left) and pouch cell (right)* ***(24)***

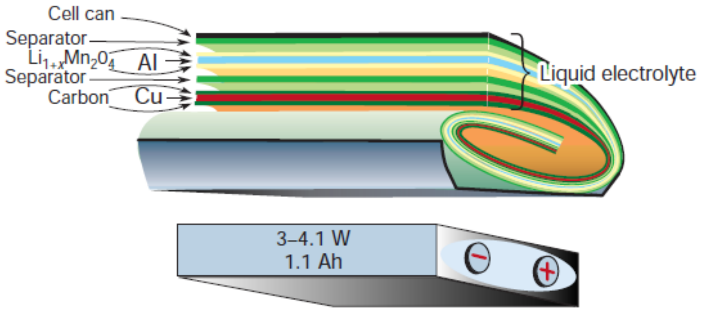
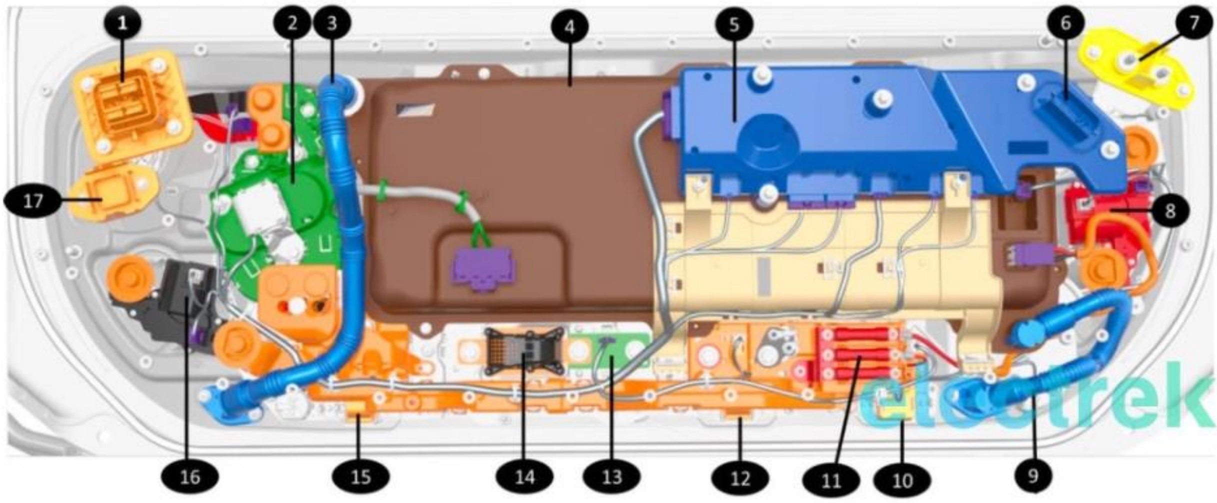


Figure 37: *The electrolyte in a prismatic cell* ***(24)***

A.3 Tesla S 2014 Housing

Figure 38: *Bottom part of the housing* ***(43)***

A.4 Tesla Model 3 Long Range Battery Pack



1. Charge port connector **2.** Fast charge contactor assembly **3.** Coolant line to PCS **4.** PCS – Power Conversion System **5.** HVC – High Voltage Controller **6.** Low voltage connector to HVC from the vehicle **7.** 12V output from PCS **8.** Positive HV power switch **9.** Coolant line to PCS **10.** HV connector to cabin heater and compressor **11**. Cabin heater, compressor and PCS DC output fuse **12.** HV connector to rear drive unit **13.** HV pyro fuse **15.** HV connector to front drive unit **16.** Negative HV power switch **17.** Connector for 3 phase AC charging

Figure 39: *The main electric components included in the Tesla Model 3 battery pack* ***(47)***

A.5 Data

A.8.1 EF-M Model

	Outer Casing						Inner Casing				Hardware	
	Vibration	**Collision**	**UV-Radiation**	**Temperature Change**	**Particles**	**Humidity**	**Heat Leakage**	**Electricity Leakage**	**Fire**	**Chemistry Leakage**	**Around Cells**	**Around Module**
BMW i3 2015	?	?	Metal	Metal	Gasket	Gasket	?	?	?	?	-	Tubes
Tesla S	?	?	Plastic, metal	Plastic, metal	Adhesive	Adhesive	?	?	Fuse, fireproof material in lid	?	Tubes	-
Tesla Model 3	Vibration pad	?	?	?	?	?	?	?	Fuse	?	Tubes	-
Nissan Leaf e+	?	?	Metal	Metal	Gasket	Gasket	?	?	?	?	Tubes	-
Chevrolet Bolt	?	?	Fiberglass, steel	Fiberglass, Steel	Silicon	Silicon	?	?	?	?	-	Plate
LION Light	?	Mechanical structure	?	?	?	?	?	?	Fuse	?	Tubes	-

Figure 40: *Summary of battery solutions*

A.8.2 Material Properties – Young's Modulus and Density

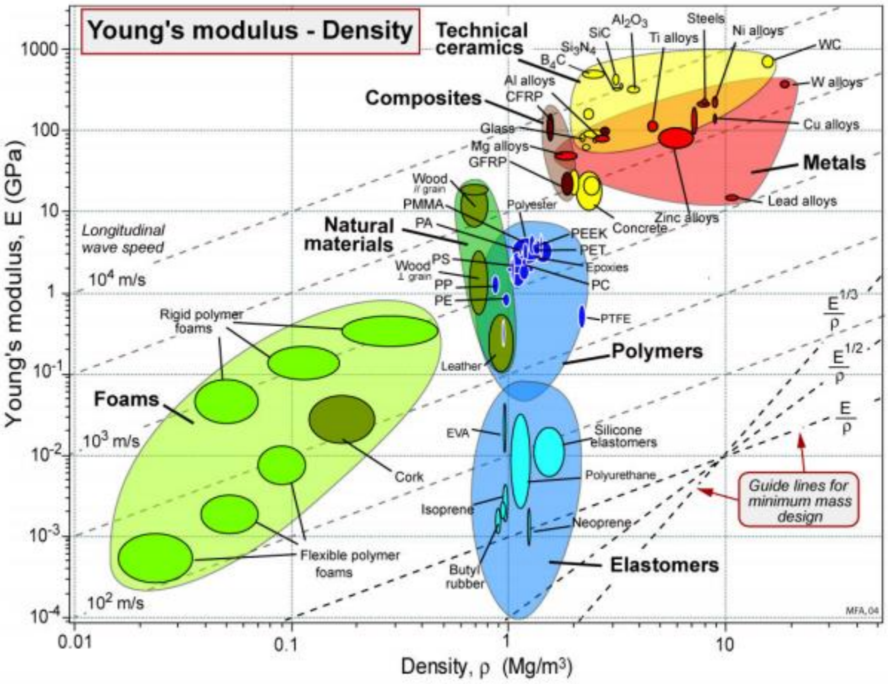


Figure 41: Diagram of Young´s modulus and density (60)

A.8.3 Material Properties – Strength and Max Service Temperature

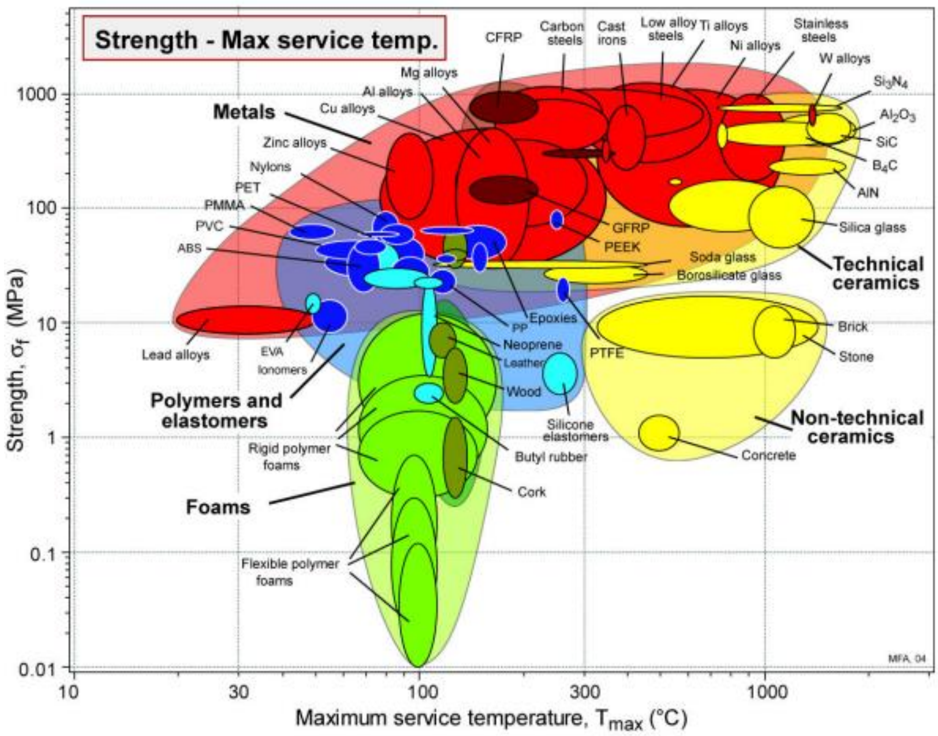


Figure 42: Diagram of strength and max service temperature (60)

A.8.4 Material Properties – Conductivity and Resistivity

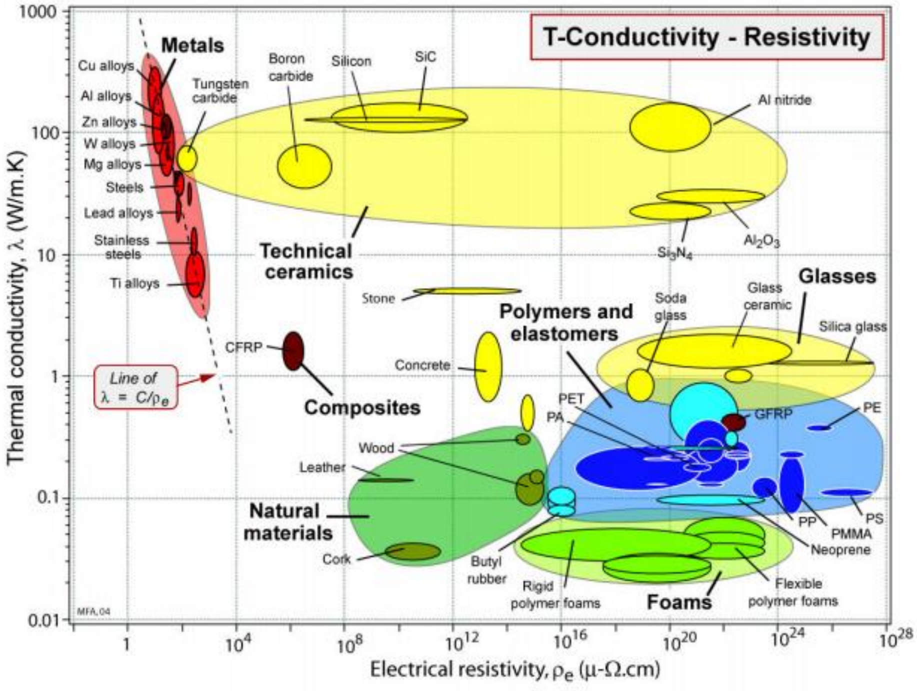


Figure 43: *Diagram of conductivity and resistivity* ***(60)***

A.8.5 Material Properties – Strength and Density

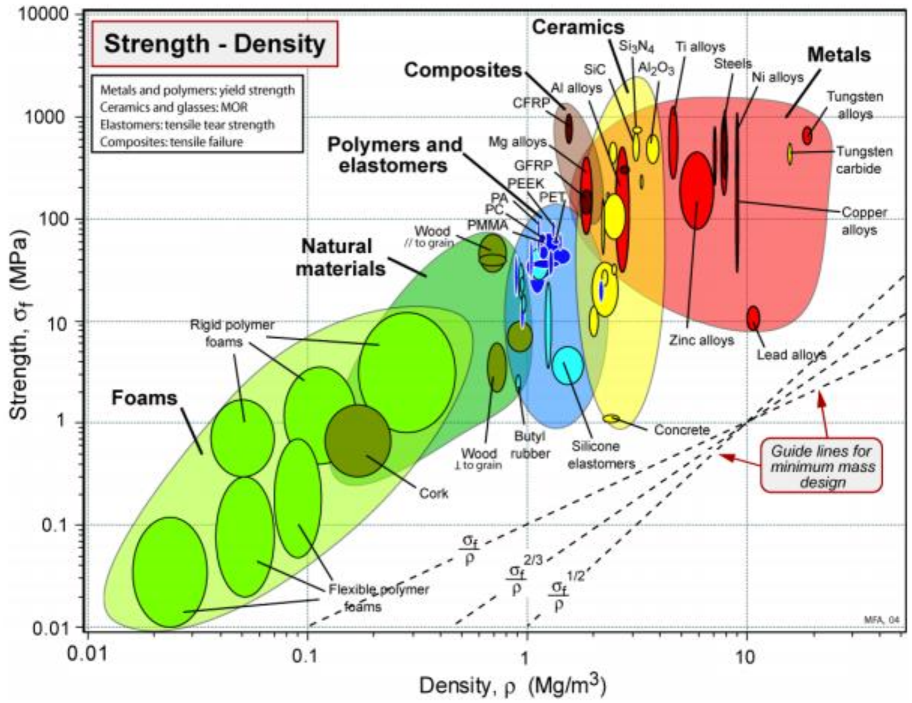


Figure 44: *Diagram of strength and density* ***(60)***