An Optimised Packaging Solution of a Battery Disconnect Unit

Master's Thesis in Product Development

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Cover:
A visualisation of a plug-in hybrid electric vehicle powertrain, more information about the architecture and the role of the battery disconnect unit can be found in Chapter 2. (Volvo Car Corporation, 2017)

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Abstract

Today, one of the largest problems regarding the environmental impact is the carbon dioxide emissions. The restrictions concerning these emission rates are getting tougher and the transportation sector needs to adapt to these changes. One approach that has shown large potential is the electrification of vehicles. The car industry is facing major challenges in order to create lighter, less expensive and more energy dense battery systems.

This master thesis presents the work of developing a high voltage disconnection unit, commonly known as a battery disconnect unit (BDU). It is a part of the high voltage battery system that can be found in all modern electric cars. The unit is an important component which functions ensure safety for the user while driving and handling the vehicle.

The master thesis work has been performed at Volvo Car Corporation in Gothenburg during the spring semester 2017. The work aimed at reducing the packaging space, weight and cost, as well as increasing serviceability, reducing the environmental impact and making it less complex to assembly. The development work followed a development work process divided in to six main phases concerning, information gathering, concept development and detail design.

The project ended up in a conceptual design, delivered as a CAD-model. The result shows that it is possible to reduce the overall weight by 29% and the overall volume by 43%. The design also shows improvements regarding assembly and serviceability. The overall cost was estimated as reduced, since assembly, manufacturing and serviceability indicates a reduction in cost.

The final design needs more testing and verification in order to validate the maturity of the its design and properties.

Some suggestions for improvements were not able to finalise due to limited time of the project, these suggestions are presented and discussed in the end of this report as further recommendations.

Acknowledgements

The work presented in this thesis was carried out at Volvo Car Corporation at the department Propulsion System Geometry in collaboration with another department, Mechanical and Electrical Design. We would like to express our gratitude towards all the people that have provided us with valuable knowledge and support throughout the project.

A special thanks to the following persons:

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At last we would like to send a greeting to our colleagues at the department of Propulsion System Geometry at Volvo Car Corporation, for welcoming us and supporting us during the project.

Gothenburg, June 2017

Magnus Bratt Svensson

Anna Engelbrektsson

Contents

List of Abbreviations

AC	Alternating Current
BECM	Battery Energy Control Management
BEV	Battery Electric Vehicle
BDU	Battery Disconnect Unit
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CIDD	Combined Inverter DCDC
CISG	Crankshaft Integrated Starter Generator
CTI	Comparative Tracking Index
DC	Direct Current
DFA	Design for Assembly
DFE	Design for Environment
DFX	Design for X
ECTS	European Credit Transfer System
ELAC	Electric AC Compressor
EREV	Extended-Range Electric Vehicles
ERAD	Electric Rear Axle Drive
FEM	Finite Element Method
HEV	Hybrid Electric Vehicle
HV	Hazardous Voltage
HVCH	High Voltage Coolant Heater
ICE	Internal Combustion Engine
IEEE	Institute of Electrical and Electronics Engineers
IEM	Inverter ERAD Module
IGM	Inverter Generator Module
LV	Low Voltage
OBC	On Board Charger
PHEV	Plug-in Hybrid Electric Vehicle
RMS	Root Mean Square
VCC	Volvo Car Corporation

1 Introduction

This chapter intends to introduce the topic of the master thesis work and the reason for why it was conducted. Objectives, delimitations and an outline of the report is also presented in this chapter.

1.1 Background

The automotive industry is facing a challenge in the strive to reduce the environmental impact. To achieve lower carbon dioxide emissions there is a need of creating more energy efficient vehicles. Volvo Car Corporation (VCC) is one of the car manufacturers leading the way to a sustainable future by electrifying their car fleet.

Volvo Car Corporation is a large automotive company which started to produce cars in 1927 in Gothenburg on the west coast of Sweden (Volvo Car Corporation, 2017). It is a global company, creating among the safest cars in the world (Volvo Car Corporation, 2017).

Recently, the company announced that their goal is to produce one million electrified cars until 2025. (Volvo Car Group, 2017) This can be seen as an important message to all the other car manufactures in the world. The company wants to be a part of the global work in order to reduce emissions from cars. The goal is also reflected in the core values of Volvo Car Corporation which are safety, quality and care for the environment. (Volvo Car Corporation, 2017).

Today's major challenge regarding electric cars is to create lighter, less expensive and more energy dense battery systems. To achieve these improvements for the whole battery system it is necessary to consider all its components.

This master thesis work has looked further in to the Battery Disconnect Unit (BDU), which is a part of the high voltage battery system. The unit is an important component which functions can be found in all modern electric vehicles. It ensures safety for the user while driving and handling the vehicle.

1.2 Problem Description

The BDU is a battery system component which main function is to disconnect the power supply from the battery package to the rest of the car, to ensure that the body of the car never gets electrified. An electric shock from a high voltage car could cause serious damage to a human body, even deadly injuries. The disconnection should occur in case of a deactivation, an accident, battery charging failure or if a component of the electrical system would fail and begin to supply the body with high voltage current.

A continuous target is to investigate if it is possible to lower the weight of components to make the car lighter and to provide the electric powered car with a longer rage. To be able to fit all products and functions in a car, the packaging space needs to be optimized. The way the parts are organised generates more or less space for passengers, luggage, other car components, etc.

One problem with the BDU, as it is placed in many cars today, is the serviceability. If the unit, or the components in it needs to be changed due to failure in the system or failure in the BDU itself, it takes longer time than desired to gain access and to change it.

The heat generated during the use of a battery system needs to be removed to protect the battery cells from overheating. A battery cell has a desired operation temperature range where lifetime and power are optimised (Ltd Woodbank Communications, 2005). Battery temperature outside of this range damages the cells. The BDU is not affected as much by the heat as the battery is.

The overall challenges with the BDU can be summed up as:

- Ensure safety for users and secondary users
- Reduce weight and space
- Facilitate serviceability
- Reduce heat and heat transfer

1.3 Purpose

The purpose of this master thesis was to develop a weight/cost optimised product that performs the functions of a BDU. The development process strived for serviceability, functionality, and manufacturability, as well as ensured a structured work process.

The project also aimed to provide knowledge and understanding of the subject for the project team. Further, to give insight of how product development projects are performed in the automotive industry.

1.4 Objectives

The main objectives for the project area (BDU) have been to:

- Investigate modularity to create a more flexible architecture
- Reduce needed packaging space by improving geometry
- Decrease weight
- Reduce cost
- Increase serviceability
- Optimise functionality
- Reduce environmental impact

When developing a product, different approaches that could enable a better design should be investigated. One of those approaches are modularity. It should first be investigated if the product could benefit of the modularity, and if yes, it should be investigated what type of modularity that is appropriate to implement. Modularity could be of high value in order to adapt to different markets with different requirements and legislations.

Reducing packaging space gives more space for other components and systems which creates a better and more advanced car.

Decreasing weight makes either the car lighter or enables the car to have more products or systems in it without adding on total weight.

Cost is one of the most controlling aspects when it comes to developing a new car. That is why it is of high importance to keep the cost as low as possible.

The BDU of today are complicated to perform a service on. With increased serviceability, the money and time spent during a service session would decrease and both the people who service the car as well as the customers would be pleased.

Optimise functionality means that the product should perform its tasks without any unnecessary complexity.

Reducing the environmental impact is a necessity to produce a sustainable product. To create a sustainable product should always be the target in product development projects.

1.5 Delimitations

The master thesis comprises 30 ECTS and it has been carried out during the spring semester of 2017. The project work was performed at Volvo Car Corporation at the department "Propulsion System Geometry". The public deliverables are delimited by a confidential agreement. However, the public deliverables contain enough non-confidential material to present the most valuable findings and to be able to meet the requirements of an examination of a master thesis work.

The product development work needed to consider several laws and vehicle standards, these were seen as boundary conditions.

Components that did not affect the BDU's geometry, design or its functionality have therefore been excluded. However, the work has included an investigation of the whole system to be able to discover new development possibilities related to placement, geometry, functionality and integration.

The expected outcome of the work was to deliver a conceptual design, a prototype and recommendations for further development work of a BDU. The prototype would be delivered in digital format and as a concept drawing, if time and resources were enough, a physical prototype would also be manufactured. The concept design should have a high grade of maturity, which means it should be able to work in theory even though it might need some modifications to be able to fit in the next generation of Volvo's electrified cars.

1.6 Outline of Report

The first chapter, contains a short background about the company where the thesis was performed, as well as an introduction to the thesis topic, its objectives and delimitations.

To be able to understand the challenges with the thesis and in order to solve them it is essential to have some basic knowledge about the system and parameters that affect it. The theory presented in Chapter 2 has the purpose of giving this knowledge. It covers a basic introduction of the common propulsion systems and configurations that exist in combination with electrified cars, as well as a more detailed description of the high-voltage system and the battery system architecture. Furthermore, some important design aspects for high-voltage electronics is brought up.

The methodology used in the master thesis is described in Chapter 3. To begin with, the phases of the development process and the approach is presented. There are six main phases that represents the process from knowledge searching to end result. Each phase is further described, including some short theory about the methods that were used and how they were used.

Chapter 4 declares the result of the development process and its phases. More details about how to interpret the results in combination to how the methods were used are given here.

A discussion regarding the task, approach and the results are presented in Chapter 5. Speculations are done about what could have been done in a different way, what was good and what was bad. There is also a special discussion in the last section of the chapter, where a discussion regarding the sustainability aspects concerning society and the environmental impact.

Finally, in Chapter 6, the thesis work is concluded and further recommendations for future work are accentuated in Chapter 7.

2 Theory

In this chapter, essential theory concerning electrified cars and design aspects regarding high voltage systems are presented. The theory is fundamental for the understanding regarding the role of the BDU, its composition, functions, communication and challenges.

2.1 Common Propulsion Systems and Configurations

The major part of the vehicles produced today are based on a conventional propulsion system with an internal combustion engine (ICE), which uses a fossil fuel as energy. Alternative propulsion systems that get more and more common are the electrical and hybrid-electric ones. These systems are characterized by the existence of an electrochemical or electrostatic energy storage system. (Guzzella & Sciarretta, 2013)

Propulsion systems that are purely electric are called electric vehicles (EVs) or battery-electric vehicles (BEVs). Simplified, the system consists of a battery and an electric motor. (Guzzella & Sciarretta, 2013)

The hybrid electric propulsion systems are characterized by two or more propulsion units and power sources. Vehicles that combine an ICE and an electric motor are called hybrid electric vehicle (HEV). The HEV generally consist of an ICE, further there are various types of electric motors, such as standard DC, Induction AC, etc. Some configurations also require a second electric machine to act as a generator. Furthermore, the most common electric energy system to use is an electrochemical battery. (Guzzella & Sciarretta, 2013)

There are also plug-in hybrids (PHEV), where the battery can be recharged from the grid, in the same way as it is for BEVs. The presented configurations are visualised in Figure 1 below.

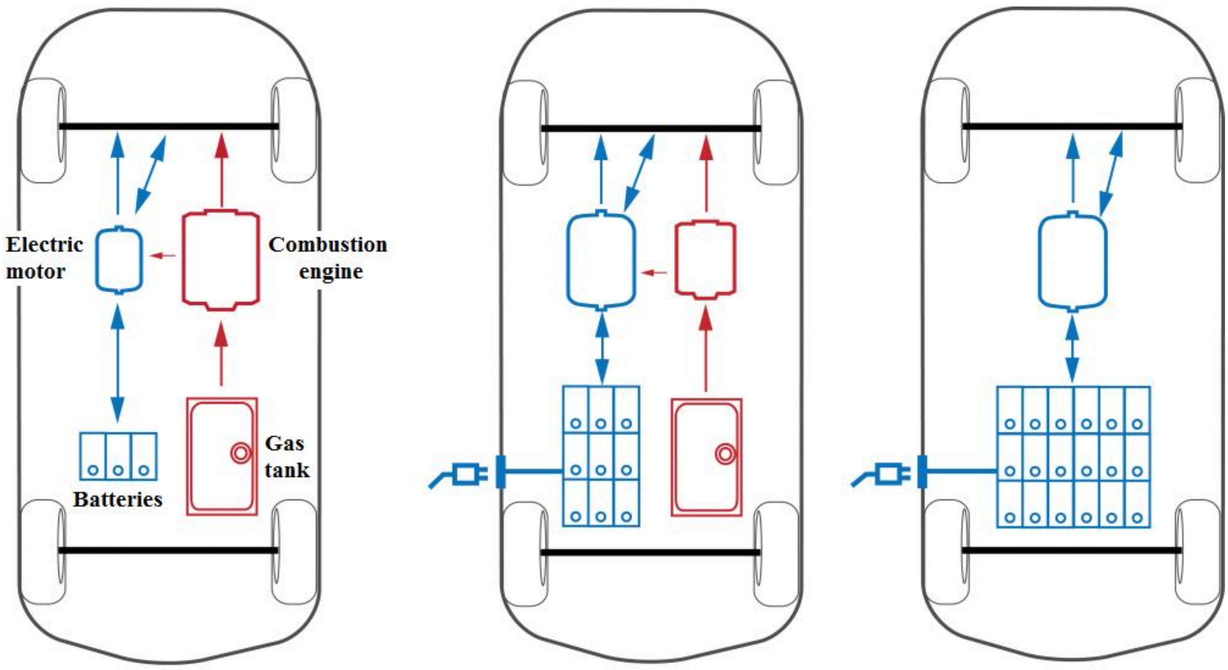


Figure 1. From left to right: HEV, PHEV and BEV. (Haldemana , Hummel, & Sigmund, 2017)

2.1.1 Types of Hybrid Configurations

There are three main types of HEVs, parallel, series and combined hybrid. Series hybrids are characterised by a configuration where the electric motor alone propels the vehicle. A battery or an engine-driven generator can work as an electricity supplier. The engine driven generator is a key component of series hybrids, as well as in the powertrain architectures referred to extended-range electric vehicles (EREVs). (Guzzella & Sciarretta, 2013)

Parallel hybrids are characterised by a configuration where both propulsion units operate on the same shaft, which allows power from one of them individually or from both' simultaneously. (Guzzella & Sciarretta, 2013)

The last type, combined hybrid, is a combined version of a series and a parallel hybrid, consisting of both a mechanical and an electric link. (Guzzella & Sciarretta, 2013)

2.1.2 Degree of Hybridization

HEVs can further be functional classified in terms of degree of hybridization, where the degree is regardless of their physical configuration. The classification is divided in micro, mild and full hybrids, also visualised in Figure 2. (Guzzella & Sciarretta, 2013)

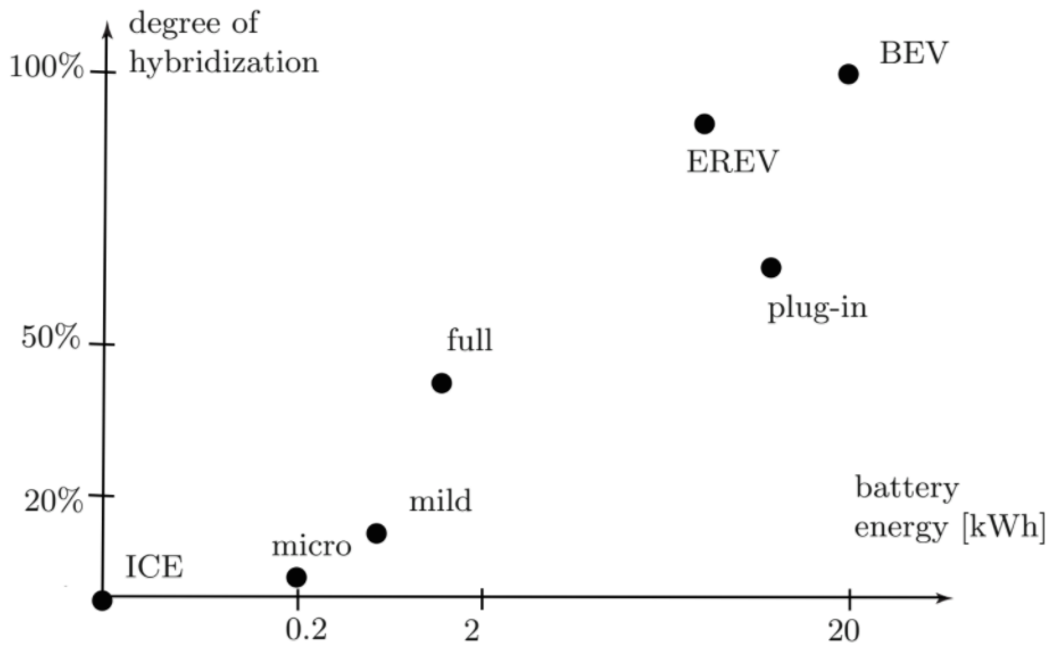


Figure 2. Classification of the HEVs in terms of degree of hybridization and battery capacity. (Guzzella & Sciarretta, 2013)

Micro hybrid is the simplest degree of hybridization. Generally, micro hybrids are characterised by the automatic engine stop-and-start, therefore they do not require a high battery capacity or complex power electronics. Mild hybrid is the intermediate degree of hybridization. A mild hybrid does not allow purely electric driving, at least not for any moderate vehicle speed. However, the electric powertrain is allowing engine boost and energy recuperation to some extent. Full hybrids allow all modes of operation, power assist, energy recuperation and purely electric driving. Further, the fully hybrids need higher levels of electric power and then use of a high voltage system with complex power electronics. (Guzzella & Sciarretta, 2013)

2.2 HV-System

The HV-system is a central part of BEVs and HEVs. The system involves hazardous voltage (HV), which for a battery pack means voltage above 60VDC. Voltage below is then considered as low voltage (LV). (Thaler & Watzenig, 2014)

The system consists of components that enables propulsion of the vehicle and acclimatisation of the coupe. An example of a HV-system for a PHEV with its main components is visualised in Figure 3 below.

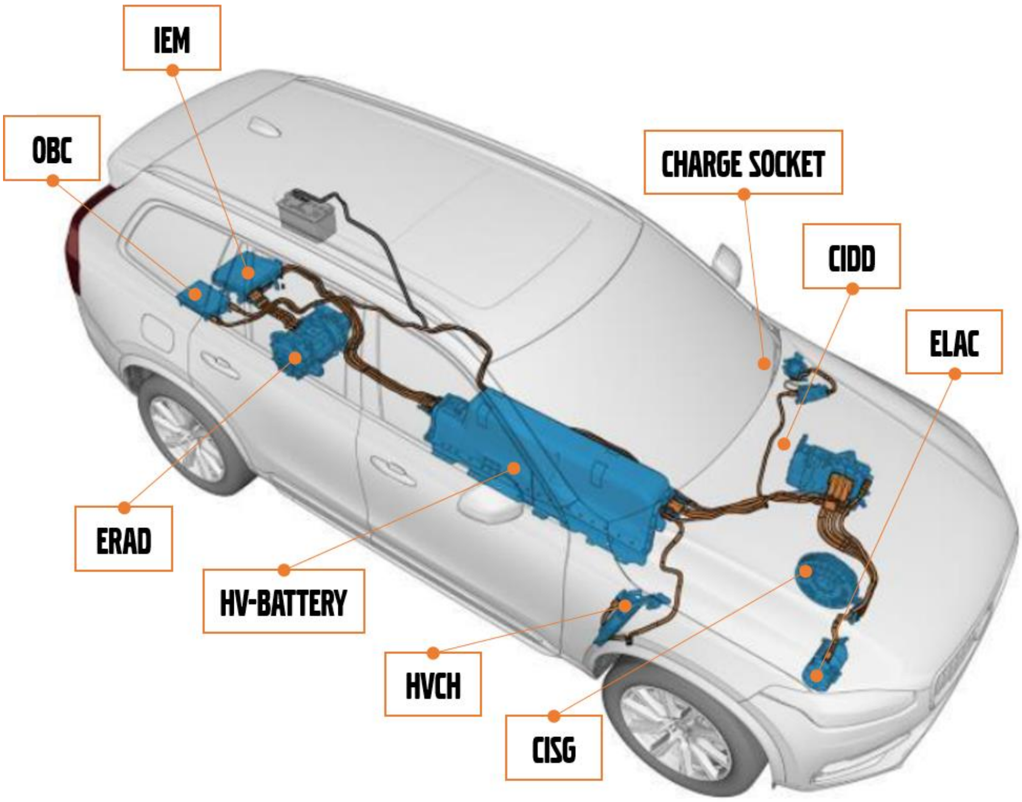


Figure 3. Example of a high voltage system for a PHEV. The car in the picture is a Volvo XC90 PHEV T8. (Volvo Car Corporation, 2015)

The HV-battery is used as the energy storage system as well as the energy power supplier to the HV-components.

The on-board charger (OBC) is the charging unit, which main purpose is to convert the AC voltage from the electricity grid to DC voltage during charging of the HV-battery. It also provides electricity to the electric AC compressor (ELAC) and the high voltage coolant heater (HVCH) during grid charging. The HVCH is active during need, in pure electric drive mode in order to heat the cooling media for the acclimatisation of the coupe. (Volvo Car Corporation, 2015)

The component that converts the battery's DC current to three phase AC current to provide power to the electric rear axle drive (ERAD) is the inverter ERAD module (IEM). Further, it also converts current in the opposite direction, AC to DC during regenerative braking of the

ERAD. The ERAD is an AC electric motor, mounted on the rear axle for propelling in pure electric and hybrid mode. (Volvo Car Corporation, 2015)

The crankshaft integrated starter generator (CISG) is used for starting the ICE and to generate current to the HV-system, as well as giving boost to the ICE if that is required. (Volvo Car Corporation, 2015)

A component named combined inverter DC-DC (CIDD), combines the inverter generator module (IGM) and the DC-DC unit. The IGM controls the CISG and converts the HV-battery's DC to three phase AC, as well as in the opposite direction AC to DC. The DC-DC unit converts HV to LV. The DC-DC is a substitute to the conventional generator driven by the ICE. (Volvo Car Corporation, 2015)

2.2.1 Battery System Architecture

The intelligence in the battery system is gathered in the Battery Management Unit (BMU), commonly also called Battery Energy Control Module (BECM). The unit controls the electrical and thermal functions and performs diagnostics on them. The electrical management includes for example charge balancing, charge determination, system voltage and current. The thermal management is monitoring and evaluating the temperatures within the system. The BECM also does insulation monitoring and it also has its central function to communicate with the other parts of the battery system as well as other parts of the vehicle. (Thaler & Watzenig, 2014)

In case of deactivation, accident or some kind of safety-critical malfunction it is necessary to be able to disconnect the HV-system from the vehicle. Then a HV-disconnector is used, which is another name for the battery disconnect unit (BDU). The BDU provides a galvanic separation of the battery pack and the vehicle, this action is performed by special HV-contactors placed at the plus and minus terminal. To provide a soft connection to the HV-circuit during activation of the system, further to prevent rise of electrical arcs, a pre-charge circuit is used. The system also includes HV-fuses, which will disconnect the battery from the HV-circuit in case of an overcurrent in order to protect the components and prevent a rise of fire. Since an overcurrent causes the fuses to be heated strongly, they should be thermally decoupled from other components, especially the battery cells to avoid overheating. (Thaler & Watzenig, 2014) The BDU and the BECM can either be integrated in the battery pack or placed outside the pack. The HV-system in Figure 3 is an example where they are integrated in the HV-battery pack.

One measurement that is used to for several inputs is the current measurement. The current is measured with a special current-sensor (I-sensor) and it is an input to the BECM to be able to determine the state-of-charge (SOC). Furthermore, also for the thermal management of the battery cells. A battery charges and discharge within special current operating ranges. In a case where the measured current is higher or lower than the specified range a disconnection should occur with interaction of the BDU and the HV-fuse. (Thaler & Watzenig, 2014)

2.3 Design Aspects for HV-Electronics

When planning and designing a HV-system it is necessary to be aware of the risks and how to prevent them. This section describes some of the parameters that is important to consider when building electrical products in order to create safe operation and handling.

2.3.1 Creepage

Creepage is defined as the minimum distance between two conductive materials measured along the surface of the insulation, see illustration in Figure 4 below. It is an important characteristic since a certain distance determines the risk of tracking, which is the flow of current along the surface of the insulation. Tracking causes heating and which leads to damage to the insulation. The breakdown of the creepage distance is a slow phenomenon, more affected by the DC or RMS voltage rather than peak events or transients. (Infineon, 2012)

An index named the Comparative Tracking Index (CTI) is used to analyse the tracking resistance properties of an insulating material. This is done by measuring the minimum voltage that causes tracking across the insulating material. (Electrotechnik, 2017)

Several parameters need to be considered to be able to decide the creepage distance; circuit type, working voltage, pollution degree, type of isolation material and its CTI value. (Infineon, 2012)

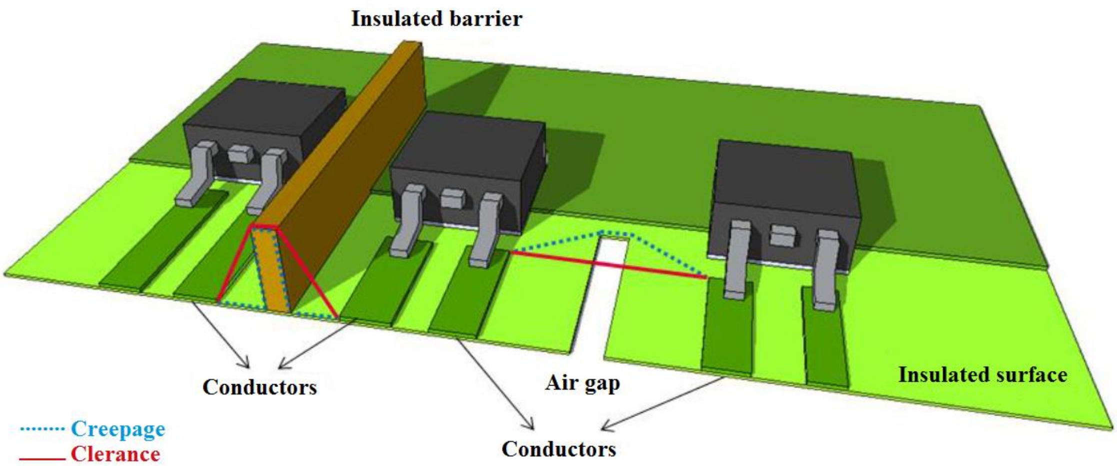


Figure 4. Illustration of creepage (along surface) and clearance (in air). (Infineon, 2012)

2.3.2 Clearance

Clearance is defined as the minimum distance between two conductive materials measured through air, see illustration in Figure 4 above. The distance determines the risk of a dielectric breakdown in air and a subsequent flashover, larger distance lowers the risk. (Electrotechnik, 2017) When a breakdown occurs along a clearance path it is a fast phenomenon that can be caused only by a short duration impulse, therefore the maximum peak voltage, including transients are used as design parameter. Several other parameters need to be considered to be able to determine the required clearance distance; working voltage, supply voltage, pollution degree, type of isolation, installation altitude, periodical transients, overvoltage category and allowable transients. (Infineon, 2012)

2.3.3 Electromagnetic Compatibility

The use of electronic systems increases in the society, for communication, automation and other purposes, not to mention in the automotive industry. This implies an increased risk for electromagnetic interference (EMI) effects and incidents. (Marksell, 2004)

Furthermore, electronic equipment must be designed to be able to operate in environments with other electronics, without being affected by external noise sources as well as not affecting the system or being a source of noise itself. (Marksell, 2004)

Another name for this is electromagnetic compatibility (EMC), which is the absence of effects due to EMI. The international definition of EMC according to IEEE is as follows: “The ability of a device, equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbance to anything in that environment.” (Marksell, 2004)

Design for EMC

In order to deal with EMI problems there are three basic elements that need to be considered, the sources of EMI, coupling and victim of EMI, see Figure 5 below.

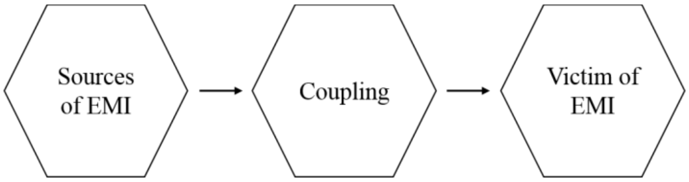


Figure 5. Three basic elements of an emitting-susceptibility situation. (Duff, 2011)

There are some common techniques that could be used in order to deal with the EMI problems. The techniques belong to different groups according to the design process and the design area. The ones that are presented below concerns the design issues that have been investigated in this thesis, which involved the mechanical design area seen in Figure 6.

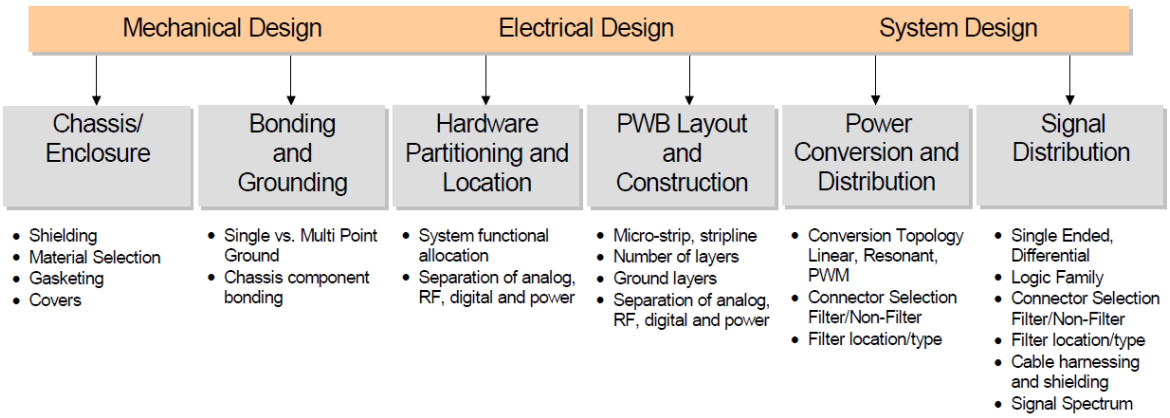


Figure 6. Suggestion of work areas in order to design for EMC. (Telephonics, 2005)

Shielding

Enclosures or housing structures are an effective way to create a shielding environment. The shielding is complementary action to filtering. To prevent a conducted coupling to appear, good filtering and circuit design is required, however there is also a need of a return path for the filtered currents. The purpose of the shield is to provide a return for the filtered current, as well as protection against direct field coupling with internal circuits and conductors. Shielding involves placing the critical parts of a circuit in an environment surrounded of a conductive surface. The electromagnetic field that couples to it will then be attenuated by a combination of absorption and reflection. (Williams, 2006)

Material Selection

When considering the choice of material for a shielding there are some important parameters that needs to be considered, one is the frequency of the magnetic field.

The shielding effectiveness for electric fields is infinite at DC and decreases with an increase in frequency. However, to shield magnetic fields are difficult due to the reflection loss. For some material and frequency combinations the reflection loss may approach zero. The magnetic field absorption and reflection loss decreases for nonmagnetic materials when the frequency decreases. Consequently, it is hard to use nonmagnetic materials to shield against magnetic fields. However, the shielding efficiency is good at higher frequencies due to both reflection and absorption losses, then the material choice becomes less important. By using materials of high conductivity such as copper and aluminium for electric (high impedance) fields, good shielding efficiency can be obtained. (Duff, 2011)

In situations where plane waves occur it is preferable to use magnetic materials since they provide better absorption loss, while good conductors (nonmagnetic materials) provide better reflection loss.

In Table 1 below a summary of the shielding effectiveness for magnetic and nonmagnetic materials are given. (Duff, 2011)

Table 1. Summary of shielding effectiveness for magnetic and nonmagnetic materials. (Duff, 2011)

Permeable materials	Frequency	Absorption loss A_{dB}, all fields	Reflection loss, R_{dB}		
			Electric fields	Magnetic fields	Plane waves
Magnetic ($\mu \geq 1000$)	Low: <1 kHz	Bad	Excellent	Fail	Good
	Medium: 1–100 kHz	Good	Good	Bad	Fair
	High: > 100 kHz	Excellent	Fair	Poor	Fair
Nonmagnetic ($\mu = 1$)	Low: <1 kHz	Fail	Excellent	Bad	Good
	Medium: 1–100 kHz	Bad	Excellent	Poor	Good
	High: > 100 kHz	Good	Good	Fair	Fair
Assumptions: Material thickness: 1/32 in Source distance: 10 ft (3 m) Radio frequency: as shown			Attenuation scores: Excellent: >150 dB Poor: 30–50 dB Good: 100–150 dB Bad: 10–30 dB Fair: 50–100 dB Fail: <10 dB		

Gasketing

The shielding effectiveness are affected by the number of fasteners, or more correctly the spacing of fasteners between different panels. In cases where effectiveness up to 1 GHz and beyond is desirable the spacing becomes very small, which compromises the serviceability and accessibility. Then a conductive path could be a preferable alternative to use, like a conductive gasket, knitted with wire mesh. The gasket could serve its purpose by being placed and sandwiched between two panels or flanges, it will then conform with irregularities of the surfaces, se alternative set-ups in Figure 7 below. Further, this ensures continuous contact across the joint which means no shield current will be diverted. The impedance of the joint and the bulk shield material should be well matched in order to achieve good shield effectiveness. (Duff, 2011)

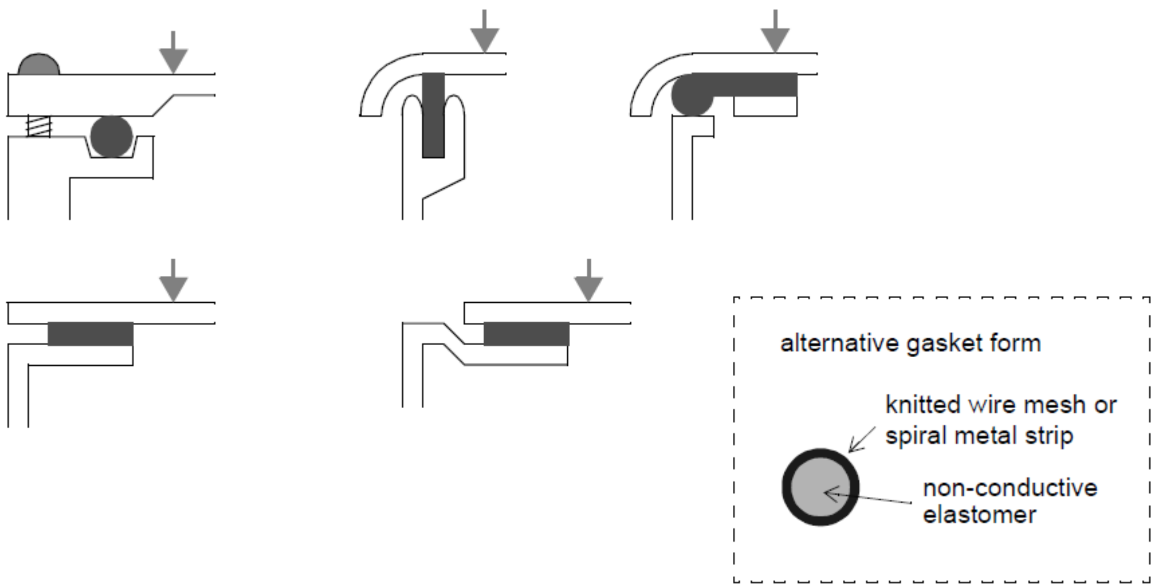


Figure 7. Alternative set-ups of conductive elastomer gaskets. (Duff, 2011)

3 Methodology

The approach of this master thesis work has followed a modified version of the product development cycle created by Ulrich and Eppinger as a literary base. It is an acknowledged set of methods and it is used in several papers. The approach agreed with the project objectives and it has a good framework for developing new products. Methods that have been considered as useful have been added to complete the base methods.

The modified development cycle contained only the first five original phases which means that the production ramp-up phase was excluded. The aim of the master thesis was to deliver a development suggestion for future product generations, therefore the last phase was considered as irrelevant. The main phases including the methods and tools for each phase are represented in Figure 8 below.

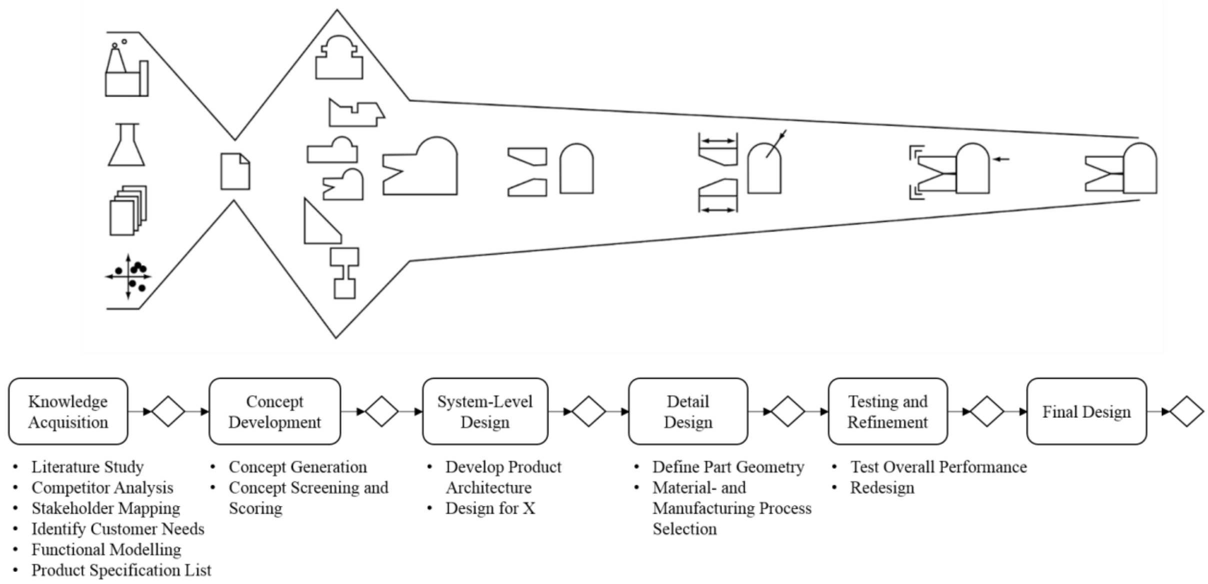


Figure 8. The modified product development process including six phases. (Ulrich & Eppinger, 2012)

The upper part of Figure 8 visualises the development funnel, which is a creation of a wide set of alternative product concepts that is narrowed down by using different methods and tools. Iterations are performed within the phases until the last phase is reached and the product is realisable. (Ulrich & Eppinger, 2012)

The following sections further describe the phases of the development process. Each phase consists of a short introduction of the methods and tools that were used, as well as what was expected from them and also how they were used in the project.

3.1 Knowledge Acquisition

This phase aimed at gathering valuable information about the BDU, its system and technology, the competitors and the customers. The methods that were used for information gathering and analysis are listed and described.

3.1.1 Literature Study

A literature study is a search for published literature, which includes trade magazines, journals, books, reports, market, consumer and product information as well as new product announcements. The most efficient way to find published literature is to perform electronic searches by searching on the internet. On internet, there also exist structured databases, which in many cases are specialised for a specific field, such as automotive. (Ulrich & Eppinger, 2012)

A literary study was performed with the purpose of getting base knowledge as well as deeper knowledge within the topic of the master thesis. A good understanding of the whole system was considered as essential to be able to make relevant decisions in further phases in the development process. The study also aimed at providing knowledge and insight in to the state of art regarding electric vehicles in general to be able to identify possible opportunities for development and to determine areas of interest. Two main theory areas were investigated; Electric and hybrid electric vehicles (powertrain configuration and HV-system) and Design Aspects for HV-electronics. The information that was gathered is summarised and presented in the Theory chapter, Chapter 2.

Information sources were mainly gathered from Chalmers library website in forms of scientific papers, articles and books. As a complementation, google searches were used to find appropriate information. The internal company website has also been used to search for specific information that is valid at Volvo Car Corporation, however some of that information is confidential and is only presented in the unpublicised version of this report.

To get even more knowledge about the problem and the system, interviews were held with persons that have knowledge within the topic. The interviews were systematically held throughout the project work in order to maintain a good communication between all the parties involved. The interviews were held in a semi-structured format, which meant that some of the questions were prepared and some were composed during the interview.

3.1.2 Competitor Analysis

To investigate the market and to compare different competitor products, a benchmark is a well-known method to use. The procedure of how to conduct a benchmark can vary depending on what the goal with the benchmark is. One method is to establish a benchmark chart with defined metrics of interest. Then the metrics values are collected for each competitive product and further inserted in the chart. Another approach is to use customer needs instead of metrics. This approach requires a collection of the customer perception data since there is rating of the relative degree to which the products satisfy the customer needs. Both methods can be very time consuming when it comes to collecting the metric data values and the customer perception data. (Ulrich & Eppinger, 2012)

The benchmark that was performed in the project was a mix of the two mentioned approaches above. The aim was to find out about the competitor's composition, design and components of the BDU, as well as the placement in the car. The collected information was inserted in a chart where both the needs and metrics were listed. Due to the time limit, no testing or disassembling was performed in order to find out information about competitors' products. The found data was therefore mainly based on information gathered from the automotive benchmark database A2mac1. As a complementation to the database, internet searches, reading articles and other sorts of papers have been performed. The car models that were benchmarked where chosen due to amount of available information, as well as modernity and type of technology.

3.1.3 Stakeholder Mapping

A stakeholder mapping is a good method to use to ensure that all the needs of everyone who will be influenced by the products and its changes are considered. The method is the first step in the mapping of the customers. The stakeholder mapping lists all the groups of people who are affected by end outcome, in this case the BDU. The first stakeholder in the list is the end user and the external customer who is the one that makes the buying decision about the product. Further it should also include other customers within the firm such as production departments, financial departments etc. (Ulrich & Eppinger, 2012)

It is also good to have a column where the impact of influence is a ranked and a column with suggestions for how to keep the stakeholder engaged. (Bullen, 2014)

The stakeholder mapping was performed according to the description above with the purpose of giving a good overview of the involved actors and what they considered as important.

3.1.4 Identify Customer Needs

To be able to develop a satisfying product, it is important to identify who the customers are and who the primary customer (e.g. the end user) and the secondary customer (e.g. service) is. The customers can be identified from the stakeholder mapping and depending on which impact the product have on the customer, a categorisation of primary and secondary customers can be performed. When the customers are known, it is time to start gathering the customer needs. By observing and interviewing the customers of interest, a list of customer needs can be set up. (Ulrich & Eppinger, 2012)

In the project, a meeting with the involved stakeholders were set up in order to find out what their needs were. No observation was performed, since the stakeholders already were aware of the needs that could have been discovered through observations. Afterwards, a customer need list was established, where each need was classified as a requirement or a desire. Requirement means that the need must be fulfilled, while desire has the purpose of being a delighter.

3.1.5 Functional Modelling

The function modelling is a method that differs depending on what type of product it is. A totally new product or a new version of a known product that should be developed, demand different approaches. With a known product, the question is which functions of the current solution that should be kept and which should be removed in the new product. If new functions are added, they should be based on the customer needs. When it has been decided what functions the product should have in general, it is preferable to decompose the functions in to sub functions. The purpose of the functional decomposition is to make it simpler to both understand and to deal with the main function, hence the sub functions together should perform the main function. These sub functions are later used as a base for concept generation. (Ulrich & Eppinger, 2012)

A functional model of a BDU was set up. The functions were mainly based on previous versions of BDUs, information gathered in the literature study was also used a basis for defining the functions. A decomposition of the functions was performed. Some functions and solutions were decided to be kept as they were in previous versions, while other were decided to be investigated and generated in the concept development phase.

3.1.6 Product Specification List

When the customer needs have been documented, a product specification list can be established. The aim of the product specification is to represent an agreement on what to strive for to satisfy the customer needs. The list should contain measurable details about what the product should do, further it should also be precise and consist of metrics and values. (Ulrich & Eppinger, 2012)

A product specification list of the BDU was given from the customer, this list was analysed and then adjusted according to the specific objectives of this master thesis work. Updating the specification list have thereafter been an iterative process during the project.

3.2 Concept Development

A product concept is an approximate description of a future product. The description normally contains the principles of how the concept should work, look like and how it should generate value for the customer. (Ulrich & Eppinger, 2012)

In this phase of the development process, the product concepts were generated. Methods and tools that were used for the concept generation, the screening and scoring are presented in this chapter.

3.2.1 Concept Generation

Brainstorming is a good method to release thoughts and ideas in an unrestrained way. The larger the amounts of ideas, the better. All ideas are good ideas in this stage and can be used as a basis for further idea generation. It is also preferable to take inspiration from different concepts and try to combine them directly after the session to create even more concepts. To get some structure in what the brainstorming should aim at it is a good idea to first start with a total system brainstorming followed by brainstorming around subsystems and end with brainstorming about the systems inside subsystems. (Ulrich & Eppinger, 2012)

The Concept Combination Table is a method that systematically combine different sub solutions in to total system solutions. A variant of this method is called Morphological matrix and is broadly used in product development processes. This systematic way of creating concepts from sub solutions, gives large numbers of different system concepts that normally should not have been thought of otherwise. The concepts are created by taking one solution from each row in the morphological matrix. The different solutions are placed in the cells of the matrix. (Weber & Condoor, 1998)

The brainstorming sessions that were performed in the project were held by the project members in collaboration with colleagues from Volvo Car Corporation in order to get a large variation of ideas.

The first brainstorming session that was performed involved only the project members. This session aimed at generating solutions for a BDU concept. Everything from total concepts to solutions for sub-systems were generated. The ideas were further discussed as well as broke down to sub solutions in order to gather the result in a concept combination table.

The session with the colleagues involved a heat problem, a short presentation of the problem was given before each person had 10 minutes to brainstorm solutions. The available tools were paper and pen. When the brainstorm was done, everyone presented their ideas. Then the boundary conditions were introduced and the concepts were further discussed, refined and documented.

3.2.2 Concept Screening and Scoring

A first step of the concept screening could be done through an Elimination matrix. This is a matrix that has the purpose to eliminate the concept alternatives that do not fulfil the most fundamental requirements of the product specification list or that are unrealisable. The elimination matrix is a form of rough screening that also investigates if the product solves the main problem, is within the cost-frames, is in line with the company's strategy and if it has any benefit according to the environmental- or security-perspective.
The concept alternatives that proceed from the Elimination matric is only the ones that fulfils all the criteria and the ones involving uncertainties that needs to be investigated further before being judged. (Johannesson, Persson, & Pettersson, 2013)

In the next step of the screening process a Pugh matrix can be used, which is a matrix where selection criteria of each concept are compared against a reference, normally the current solution. The criteria should represent the most important requirements and needs, to ensure that the result will meet these ones. The method is a quick evaluation aiming at selecting a few concepts with high potential, from a large amount of different solutions. The concepts could pass the Pugh matrix by being a promising concept or by being a promising concept when combined with another concept. (Ulrich & Eppinger, 2012)

To reduce the number of concepts even more it is preferable to use a Kesselring matrix. A Kesselring matrix is similar to a Pugh matrix but instead of just scoring the concepts compared to a reference the scoring criteria are weighted and rated according to the grade of importance. The Kesselring matrix are normally used as a second stage of screening due to the higher complexity compared to Pugh. When the Kesselring matrix has been performed there will only be one or a few concepts left to pass to the development stage. (Ulrich & Eppinger, 2012)

Elimination matrices were used in the project to get a manageable number of concepts and also to get rid of the ones that did not even fulfil the fundamental requirements.

The Pugh matrix method were used several times to screen out the most promising concepts. In the second rounds, the references were changed in order to see the validity of the first result. The most promising concepts that proceeded from the Pugh matrix continued to the last screening round where the Kesselring matrix were used.

3.3 System-Level Design

The system-level-design phase aims to further develop the chosen concept/concepts from the concept development phase by developing a product architecture. Furthermore, by decomposing the product in to subsystems and components.

3.3.1 Develop a Product Architecture

The product architecture is the layout of the system and it has the purpose of describing how different subsystems are connected to each other and how they interact. The way the architecture is designed have a large impact on how adaptable the product is to different needs and requirements. If the subsystems are integrated it often means that it is possible to optimise packaging space, weight and functionality. A modular architecture is less internally dependent and thereby allows higher flexibility without having to change a large amount of parts. The possibility to carry over more subsystems from earlier models and by that save development time and cost are another advantage of modular architecture. A modular product architecture could have different meanings. One is scalable modularity, it could also be common interfaces that enables different parts to fit in the same geometry or other solutions that enables the same functions with many carryovers. (Ulrich K. , 1993)

Establishing the architecture can be made in a four-step method. These four steps help structuring the decision process. The first step is to create a schematic of the product followed by clustering the elements of the schematic and then create a rough geometric layout of the system ending with identifying the fundamental and incremental interactions between clusters. (Ulrich & Eppinger, 2012)

The first step, create a schematic of the product, is performed to create understanding among the team about how the product are put together and how it interacts between elements to perform the functions of the product. (Ulrich & Eppinger, 2012)

In this project, the first step was done by adding information to the already existing electrical diagram of the BDU provided by VCC. The function and modelling diagram made earlier in the process was integrated in to the electrical diagram to explain the functions of the different parts. This created a good visible base for discussions and for understanding of the system.

The second step, cluster the elements of the schematic, helps to decide whether to cluster or not to consider a number of factors. These factors are:

- Geometric integration and precision

  Chunking elements together allows a single element or a group of elements to control the physical relations between the elements. Elements that have to be placed at a precise location or having a close geometric integration should be placed together.

- Function sharing

  When several elements/parts could be clustered together in to one physical component and still perform all functions of all the elements, then they should be clustered together.

- Similarity of design or production technology

  Elements that have the similar design or production technology should be clustered together due to economic advantages in design and/or productions. One example is electronic elements that clustered together could be placed on a circuit board for more effective packaging, better function and ease of handling in production.

- Localisation of change

  If an element should be involved in a major redesign it should be separated as an own chunk not to disrupt the elements around it.

- Accommodating variety

  Making a product flexible to fit different standards and needs by clustering a number of elements is a good approach. This cluster of elements could be changed depending on the market or customer to create more value for the customer.

- Enabling standardization

  If a group of elements could be used in several products, they should be clustered together in to one single chunk. This chunk could be made in greater numbers and the producer can take advantage of the scale of economy.

- Portability of the interfaces

  Depending on the interactions between different elements they should be placed close to each other or could be placed far from each other. For instance, an electrical interaction is insensitive for distances compared to mechanical interactions. This means that elements with sensitive interactions, like mechanical interactions, should be clustered close together.

(Ulrich & Eppinger, 2012)

Which factors that matched the BDU's different elements the best was investigated by discussing the different factors for each element. Sometimes more than one factor suits the element and then it had to be decided which cluster to add the element to.

In the third step, a rough geometric layout in 2D or 3D is created to more easily see if the geometric interfaces are feasible or not and if the elements fits together physically. These layouts could be drawings on a paper, physical models (made of cardboard, foam or in a 3D printer for example), or computer models.

In this project, the geometric layouts were first drawn on paper to get the 2D perspective correct before proceeding with the 3D drawings. It was found to be easier to change and discuss around a simple paper drawing. Some of the 2D sketches were then transformer in to computer models to get the complete 3D perspective.

The fourth and last step is to identify the fundamental and incidental interactions. This step is made to give further information about the system to the teams working with the different chunks. The more they know about how the system interacts, the better. The fundamental interactions are the basic physical interactions for instance. The incidental interactions on the other hand are not that easy to detect. It could for example be vibrations, heat, radiation or magnetic fields. (Ulrich & Eppinger, 2012)

How the BDU's components are interacting was analyses by first writing down the fundamental interactions by looking at the physical connections between the components. The next step was to find out which incidental interactions that are present between the parts. In this stage, much more knowledge gained from the knowledge acquisition was used to understand and analyse the interactions.

3.3.2 Design for X

Design for X is a well-known method that has the purpose to increase the awareness of how the product is designed in order to prepare the product for certain aspects (X) (Ulrich & Eppinger, 2012). This project has focused on the aspects that were considered to increase the value of the BDU and its lifecycle. The chosen aspects were design for assembly/serviceability and design for environment, these aspects are further described in the sections below.

The method worked as a mind-set throughout the development phase. By having this approach and by checking against the aspects in the decision makings, the method ensured that the design for X aspects were considered.

Design for Assembly / Serviceability

Some areas are more affected by the product architecture than others. In the assembly stage, it is crucial that the product architecture is made with assembling in mind to get high effectiveness during the assembly operation. It should also be easy to disassemble the product, this is where the serviceability aspect comes in. Easy assembling and good serviceability should be considered at the same time, since they affect each other.

The demand on design for assembly varies a lot between manually assembled products and products that are assembled by machines. A machine could be programmed to remember in which order and at which position parts should be installed regardless of how many movements it should perform. In the case where an operator should assemble a product, a more intuitive assembly scheme is preferable to shorten the time of learning and to make the assembling more mistake-proof. (University of Wisconsin, 2017)

An effective assembly scheme saves both money and time if it is done properly. The serviceability and the physical ergonomics increases for the people maintaining and installing the unit with a thought through assembly scheme.

Both the internal assembly, putting the components together to form a product, as well as the external assembly, installing the unit in to the car, have been analysed in this project. The assembly scheme is based on aspects like cognitive understanding of sequence, assembly time and physical aspects.

Design for Environment

The total environmental impact depends on several different aspects. A broad perspective is needed to create a product that are environmental friendly in as many aspects as possible.

Starting with the material choice where a lot can be made to get a more environmental friendly product. The material could be environmental friendly in different aspects, it could be nontoxic, possible to recycle, demand only small amounts of energy to produce, biological etc.

The energy needed to produce the product and to use the product should be as low as possible. This energy should be made from a clean energy source that is as friendly to the environment as possible. A clean energy source is normally where nature is used as a source like the solar, wind or water power. Consuming waste gases and waste heat could be seen as a green source of energy like landfill off-gassing for instance. (IGS , 2017)
During its life-cycle a product should contribute with as low levels of emissions as possible. When a product is produced, the emissions from the factory should be kept low to not pollute the environment, same goes for use and destruction/reuse. (Ulrich & Eppinger, 2012)

How a product is put together can also influence the possibility of a proper recycling. Preferably it should be easy to take apart the product, as well as separating the different materials from each other in order to recycle them separately. (Ulrich & Eppinger, 2012)

A lot of products using glue or other adhesives to assembly their products. Adhesives have a lot of advantages, however recyclability are not one of them. Mixing materials and glue them together is not a preferable way to assemble products if the environment should be prioritised. Some composites that mixing different materials are not a good choice either when it comes to recyclability. (Autodesk, 2017)

Summarised, the DFE process are segmented in to a number of stages. These stages are in short; plan the DFE, identify potential impacts, select guidelines, apply guidelines, design with DFE in mind and reflect upon process and results. All these stages were touched upon during this project and the BDU is designed with environment in mind.

3.4 Detail Design

The detail design phase includes step that creates specification of the parts, manufacturing processes and materials.

3.4.1 Define Part Geometry

In this stage, a design/geometry based on earlier findings is created. This design should include all functions and components stated in the final System-Level Design. The geometry should be designed to fit the available space in the car where the product should be installed. It should also be large enough to fit all components and make sure that they get enough space for cooling and expansion.

The components of the BDU were at first created in a digital environment, in the CAD software CATIA V5, in order to have the possibility to make fast changes and to save money.

3.4.2 Material- and Manufacturing Process Selection

To obtain proper quality and a functional product, it is important to consider the manufacturing process while selecting material and wise versa.

CES EduPack is a software that can be used to decide which material that best fulfils the requirements of a product. The program could interpret the input data and then provide the user with trade-off curves that could be used as basis for decisions. The program also has a feature that suggests manufacturing methods depending on the chosen material and other parameters as cost or volume. It is also possible to do the opposite, decide material depending on cost, volume or/and manufacturing process. (Granta, 2017)

In the project, CES was used as a source and guidance in decision making and information gathering. First step involved setting up requirements and constraints for each component concerning the materials and the manufacturing processes. Then the requirements were used in order to create charts of material alternatives and further to be able to suggest an appropriate material. Then a screening process started were suitable materials were compared. Further, when a material was selected for a specific component, different manufacturing methods were investigated and information about them was documented. Finally, a manufacturing process that was considered as suitable according to the material and process specifications was selected.

3.5 Testing and Refinement

This section aims to describe the testing of the construction, how well it meets the requirements and needs. If any defects are found in the design it should be changed until the construction fulfils the needs. The environmental impact will be assessed as an aspect in the redesign.

Simplified FEM-calculations is a method that can be used in order to verify if the chosen combination of geometry and materials can handle the loads applied on the structure. This is a fast and simple way to evaluate the structure and the program also has the possibility to provide good input on where to add or remove material to optimise the structure.

To test if the product fits within the main structure, which in this case is the car, it will be mounted in the car in a digital environment. Assembly tests can also be performed in the digital environment.

The design changes that were conducted were based on the analyses from the testing results. Furthermore, feedback was gathered from stakeholders to ensure that they were satisfied with the result.

3.6 Final Design

The final design phase is the last phase in the product development process and this phase is more of a summation step where everything is documented and specified for the last time.

The final design was checked against the customer needs and product specification list, in order to know if they were fulfilled or not. A bill of material was set including type of product, materials and number of components. A final assembly scheme was also defined.

4 Results

This chapter presents all the findings in the project. The result follows the same structure as Chapter 3, where the phases are used as a guidance in order to follow the development process.

4.1 Knowledge Acquisition

In order to get more knowledge about the system and its composition a knowledge acquisition was performed. The result from this phase is presented in this section.

4.1.1 Competitor Analysis

The competitor analysis was made through a benchmark. It was found that the electrical systems differ a lot between car brands and between models inside the same brand. Both the name of the systems and the location of the components differs. This made it hard to benchmark the BDU separately. In some of the benchmarked cars the BDU is no more than a fuse box and does not serve any other purpose. In other cars, the BDU is the centre of battery control and everything concerning the control of the battery passes through the BDU. This makes it hard to compare unit to unit between brands. However, some aspects can be investigated and have been done in this benchmark.

The BDU-subsystem was seldom named BDU in the system-tree on the A2Mac database neither was it always placed in one box. The approach to benchmark the BDU independent of the configuration was to isolate the components and the functions of a BDU. Due to this, the areas examined in the benchmark is the BDU as Volvo Cars have chosen to describe a BDU which is a box/boxes containing large fuses and large contactors with the function to disconnect the battery from the rest of the car in case of an error or accident. The procedure to find the BDU in the system-tree of a car model at A2Mac was to search for these type of components, investigate the system by looking at pictures and connection schemes to see what functions that were involved.

The established benchmark chart can be seen in Table 2 below. From this chart a better understanding is given of how different car manufacturers have chosen to design their BDU’s with consideration of placement in the car, size, weight, choice of material and component requirement. The question marks in the chart represents unknown values, attributes or properties. The reason why they are unknown are lack of information in text, on labels or no picture showing the attribute of a part.

Table 2. Benchmark table with information about competitors BDUs.

Metric No.	Metric	Units	**Acura** RLX 2014	**Audi** A3 1,4l e-Tron 2016	**BMW** i3 eDrive Range Extender 2014	**Chevreolet** Volt 1.5 2016	**Ford** Fusion 2,0 2013
1	Degree of electrification	-	MHEV	PHEV	PHEV/ REEV	PHEV	FHEV
2	Electric power output	kW	89	75	125	111	88
3	Location of HV-battery	-	Trunk	Under Backseat	Cupé Floor	T-Tunnel	Trunk
4	Location of BDU	-	Inside the battery casing	Inside the battery casing	Inside the battery casing	Inside the battery casing	Inside the battery casing
5	HV-Battery Voltage and output	V/kWh	260/1,3	355/8,8	362,9/18,8	300/18,4	280/1,4
6	Sevice lid (Easy to access)	-	?	No	No	No	Yes
7	Volume (estimated)	dm^3	4,69	5,66	6,16	4,42	2,19
8	Total mass HV-disconnect	kg	2,25	2,52	2,66	1,96	1,27
9	EMC shielding (material)	-	Steel	Metal + Plastic	Aluminium	? (Plastic)	Steel
10	MSD-placement	-	Back of battery	?	?	1 in front of BP + 1 on top of BP Between the front seats with integrated fuse 350A/420V	Front of battery (Behind back seats) Integrated Fuse 125A/?V
11	No. Of fuse	pcs	2	1	1	4	1
12	Fuse spec.	A/V	200/400	250/450	350/450	10/450	30/?
	Fuse spec.	A/V	30/450			15/450	
	Fuse spec.	A/V				30/450	
	Fuse spec.	A/V				40/425	
13	No. Of lid fastener unit	pcs	0	0	0	3	0
14	No. Of contactor/relay	pcs	3	3	2	4	3
15	Current sensor placement	-	Outside (DC-DC convert)	Inside BDU	?	Inside BDU	Inside BDU

Metric No.	Metric	Units	**Mitsubishi** i-MiEV 2011	**Nissan** Leaf 2011	**Tesla** Model S P60D 2013	**Toyota** Prius Four Touring 2016	**Volkswagen** e-Golf VII SEL Premium 2015	**Volvo** XC90 T8 2016
1	Degree of electrification	-	BEV	BEV	BEV	PHEV	BEV	PHEV
2	Electric power output	kW	47	80	225	53	85	85
3	Location of HV-battery	-	Cupé Floor	Cupé Floor	Cupé Floor	In trunk/back seat	Trunk & floor & Tunnel	Tunnel
4	Location of BDU	-	Inside the battery casing	Inside the battery casing	Outside battery casing	Inside the battery casing	Inside the battery casing	Inside the battery casing
5	HV-Battery Voltage and output	V/kWh	324/16	360/24	350/60	600/0,7/8,8	355/24,2	400/9,3
6	Sevice lid (Easy to access)	-	No	No	?	Yes	No	No
7	Volume (estimated)	dm^3	4,10	3,36	13,50	1,72	11,33	6,41
8	Total mass HV-disconnect	kg	3,18	3,11	4,64	0,76	4,25	2,98
9	EMC shielding (material)	-	? (PP-GF30)	Steel	Aluminium	Steel	Aluminium	Steel
10	MSD-placement	-	On top of battery, access below the driverseat (left)	Middle of battery pack, middle of car under seat // Fuse 225A/450V	Engine room (LV-disconnect)	?	?	Between feet floor in the backseat
11	No. Of fuse	pcs	2	1	2	1	1	4
12	Fuse spec.	A/V	280/500	225/450	100/500	125/?	350/450	250/450
	Fuse spec.	A/V	50/500		50/500			150/450
	Fuse spec.	A/V						40/450
	Fuse spec.	A/V						20/450
13	No. Of lid fastener unit	pcs	6	0	6	4	3	1
14	No. Of contactor/relay	pcs	2	3	2	3	5	3
15	Current sensor placement	-	Inside BDU	Inside BDU	Outside BDU	?	Inside BDU	Inside BDU

There are some conclusions that could be drawn from this benchmark. Most of the car manufacturers have chosen to place their BDUs inside the battery casing, the only car that have an external BDU is the Tesla. The reasons for this is not obvious but could be space/geometry related due to the large battery capacity compared to the other cars and because it is the largest BDU in the benchmark.

The most common materials to handle the EMC shielding in the benchmarked cars are steel or aluminium. Some manufacturers did have plastic shells both around the BDU and the battery. In those cases, it is hard to see how they solved the issue with EMC shielding. They could have used a EMC coating of some kind or a composite with EMC shielding properties, but this is just hypotheses.

The number of fuses differs between one and four. This does not mean that the cars with only one fuse in the BDU only have one fuse for the whole HV-system. The only thing that could be said is that the other fuses is not inside the BDU and does not require space in the BDU. The same scenario is also valid for the contactors.

The sizes of the fuses are all larger in voltage than the HV-battery voltage, however by how much differs a lot and there is normally one large fuse together with a number of smaller fuses.

It was also discovered that the current sensor normally is placed inside the BDU. The reason for this could be that it might have to do with the precision in the current measuring.

To summarize the benchmark, it could be said that different car manufacturers have different approaches for the electrification of their car fleet. Some car manufacturers uses hybrid drivelines to get better fuel consumption and better acceleration with a less powerful combustion engine. Other manufacturers go for the fully electric cars without any combustion engine connected to the drivetrain. Inside these approaches there are a lot of different configurations concerning range extenders, multiple engines, battery sizes and regenerative breaking to mention a few. All these different approaches changes what kind of parts that the system consists of.
All these aspects made it difficult to benchmark the BDU system. The reason for this could be tracked down to this systems immaturity and fast transformation.

4.1.2 Stakeholder Mapping

The stakeholder mapping that was performed involved four different stakeholders. A chart was set up in order to gather information about them, concerning degree of impact on stakeholder, degree of influence from stakeholder, needs and engagement, see Table 3. The main stakeholder was the company, VCC, they were also the primary customer since they determined the main requirements of the end solution, as well as they should approve the product before implementing it in the car. Therefore, they also had a high influence on the project.

Assembly line, service and aftermarket were secondary customers. Ergonomics, easy assembling and serviceability were considered as the most important needs for them.

The end user is not directly affected by the BDU and were therefore not considered as the primary customer. On the other hand, if the design of the BDU is lightweight, then the fuel consumption and the emission rates would be kept at lower levels and that would affect the end user. Otherwise, a working product and security were considered as important for the end user.

Table 3. Stakeholder mapping of the involved actors concerning the BDU.

Stakeholder Name	Impact	Influence	What is important to the stakeholder?	How could the stakeholder contribute to the project?	How could the stakeholder block the project?	Strategy for engaging the stakeholder
Volvo Car Corporation	Medium	High	The end solution meets their requirements	Expertise within the field	Not giving enough information and changes their needs during the project	Continuous meetings with involved persons at VCC
Assembly Line	High	Medium	Easy to assemble, good ergonomics	Communicate their needs	Making complaints at assembly issues after finial design, instead of telling them in test phase	Reserach: Design for Assembly
Service and Aftermarket	High	Medium	Maximising serviceability, good ergonomics	Communicate their needs	Making complaints at quality of service after finial design, instead of telling them in test phase	Research: Design for Service
End user (car owner)	High	Low	Working product, security	Communicate their needs	If they stop buying/ electrified cars	Identify customer needs

4.1.3 Identified Customer Needs

The customer needs for the final product were decided together with the primary customer, which from the stakeholder mapping was identified as VCC. The needs from the other stakeholders had been communicated to VCC and were therefore also included. Eleven customer needs were identified and classified as requirements or desires, see Table 4 below.

Table 4. List of customer needs for the final product, identified as requirements or desires.

Customer Needs	Requirement (R) / Desire (D)
1. Lower volume than the current solution	R
2. Low cost	D
3. Lower weight than current solution	R
4. Low heat transfer	D
5. Easy to service	D
6. Easy to manufacture	R
7. Easy to assemble	R
8. Environmental friendly	D
9. Low number of components	D
10. Higher grade of modularity/ Flexible design	D
11. Meet legislations and standards regarding electrified cars	R

4.1.4 Functional Modell

From the functional modelling, a schematic tree diagram of a HV-disconnection (BDU) was established, see Figure 9 below. The top of the diagram represents the main function which is to "disconnect the battery from HV-system", further this function is decomposed in to sub functions. Each level of a function has a sublevel which contains a part that is able to perform the level of function. The green marked parts are solutions that were decided to be kept from previous design. This decision was taken with consideration to the objectives of the master thesis, as well as to the potential to come up with a better solution than it is today. The objectives regarding geometry, weight and cost and not specifically to invent new solutions of how to solve e.g. electrical functions. The potential chance to come up with even better electrical solution than it is today were seen as low.

The part solutions visualised with question marks, were considered to have higher potential to get better solutions than todays' solutions. The question marks purpose is to illustrate that they then were unknown solutions. Further, this meant that different solution alternatives that answer to the sub functions needed to be generated in order to solve the question marks. This generation is performed in the phase, Concept Development, found in Section 4.2.

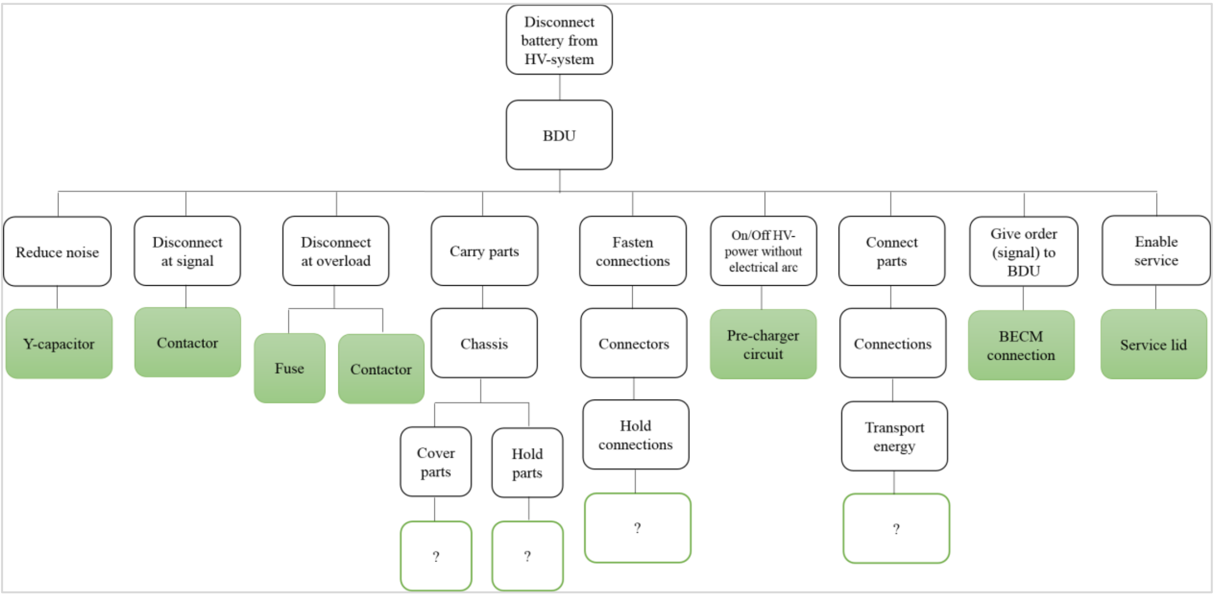


Figure 9. Functional modelling diagram of a HV-disconnection (BDU).

The sub function "Cover parts (CP)" involve water, dust and moist protection. The cover should also work as an EMC enclosure, which means it should protect the BDU from EMI as well as prevent it to send out EMI. One more parameter that was found to be an issue was the heat creation within the BDU.

To secure the parts in specific positions, the sub function "Hold parts (HP)" needs a solution. Enough force need to be applied in order to fix the parts and to prevent them from moving.

The connections need to be fasten in order to enable a failsafe construction. Furthermore, the sub function "Hold inside connections (HC)" needed a solution that enabled continuous galvanic connection.

To be able to have a functional BDU it is also necessary to have a solution to the sub function "Transport energy (TE)". The solution should enable transportation of the electrical energy between the inner parts, as well to outer parts related to other subsystems.

4.1.5 Established Product Specification List

A product specification list was established to gather important requirements concerning e.g. standards and legislations, service and aftermarket, environment etc. The list was mainly based on the requirement list given from VCC. The most important requirements and desires of the BDU were listed with consideration to the thesis' objectives and delimitations. The product specification list can be found in Appendix A.

4.2 Concept Development

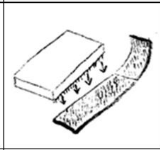
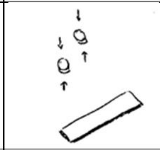
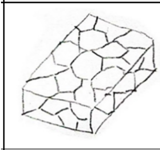
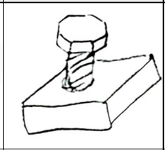
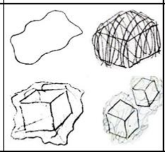
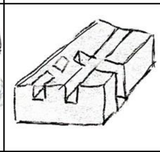
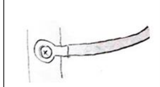
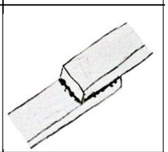
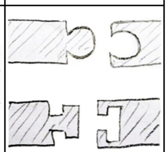
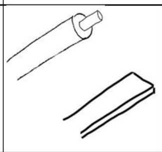
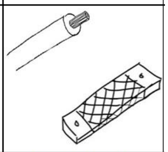
This section presents the results from the generation, screening and scoring sessions. The section is divided in two main areas, one concerning the total solution and another one about a sub-solution.

4.2.1 Generated Concepts of Total Solutions

From the functional modelling diagram, seen in Figure 9, four unknown function solutions were identified. Brainstorm sessions were performed for these functions and the result was gathered in a concept combination matrix. In total, the matrix resulted in 5376 concept combinations. Although, this high amount was considered to be hard to proceed with and to manage. To get a manageable amount, similar concepts were identified and composed, the matrix was then condensed to 864[1] combinations, a section of matrix can be seen in Table 5 below, complete version can be found in Appendix B. Each row of the matrix represents the sub-function group and each column represents the number of alternatives.

[1] From Table 5, The number of solution alternatives in each row are multiplied, i.e. 12HP x 3CP x 12HC x 2TE = 864 combinations

Table 5. The concept combination matrix when similar concepts had been combined. Complete version can be found in Appendix B.

Sub- function		1	2		10	11	12
Hold Parts	**HP**						
		Velcro (under or over)	Magnet		Formable net	Screw	Mounting rail
Cover Parts	**CP**						
		Flexible/Film cover (Vacuum bag, thin film, tape wrap, melt glue, silicone, rubber)	Hard structure cover (Plasic, Honeycomb, Metal)				
Hold inside conncections	**HC**						
		Screw	Soldering/Glueing		Mounting rail	Snap lock connection	Puzzle (With cover to lock)
Transport energy	**TE**						
		Solid cable/ Solid busbar	Stranded cable/ Flexible busbar/ Laminal busbar	……..			

4.2.2 Evaluated Concepts of Total Solutions

Further a rough screening in form of an elimination matrix was performed for the function "Hold inside connections (HC)" in order to get rid of alternatives that do not fulfil even the fundamental criteria. The other functions were considered to already have feasible solutions. In Table 6 below a section of the result from the elimination is visualised, complete version can be seen in Appendix C. In the matrix Y stands for yes, which means that the criteria is fulfilled, the opposite for N, No, criteria not fulfilled. If there were some uncertainties about whether the criteria were fulfilled or not, it was marked with a question mark. The uncertainty could occur due to lack of information or dubiousness on the concept.

Only the concepts without any N passed to the next stage. For the function" Hold inside connections" it was important to fulfil all the criteria since the goal was not to invent a new solution for this, more to find a good already common and proven solution, therefore concepts with uncertainties did not pass due to uncertainty even if they scored high.

The elimination resulted in three solutions that were evaluated as inexpensive, proven solutions, simple to implement and involved no question marks.

Table 6. Elimination matrix of the function "Hold inner connections (HC)". Complete version can be seen in Appendix C.

Elimination matrix for HC:					
Criteria fulfilment	**HC1**	**HC2**	**HC3**	**HC11**	**HC12**
Solves main problem	Y	Y	Y	Y	Y
Fulfils all standards	Y	Y	Y	Y	?
Realizable/Compatible	Y	Y	Y	?	Y
Reasonable cost	Y	Y	Y	N	N
Safe/failsafe	Y	Y	Y	Y	?
Enough resources/information	Y	Y	Y	Y	Y
Low volume/weight	Y	Y	Y	Y	?
Sum of all Yes (Y)	7	7	7	5	3
Sum of all No (N)	0	0	0	1	1
Sum of all "more info is needed" (?)	0	0	0	1	3
Total Score	7	7	7	4	2
Comments/ Pros & Cons:	**Pros:** Simple & proven solution Serviceability **Cons:** High assembly time	**Pros:** Simple & proven solution **Cons:** High assembly time Serviceability	**Pros:** Simple & proven solution Serviceability **Cons:** High assembly time	**Pros:** Smart lock function Known principle **Cons:** Expensive Complex solution Manufacturability	**Pros:** Short assembly time Serviceability **Cons:** Unsure volume of lock mechanism Unsure contact properties
Decision / Further Development:	Y	Y	Y	N	N

At this stage, the number of concept combinations were condensed to 216, which was considered to be a manageable number to be able to proceed to the next step of the screening, which was the combination evaluation. Instead of performing a screening on all the possible combinations it was decided to start with evaluating the combination alternatives for the functions "Cover parts (CP)" and "Hold Parts (HP)", since these two functions belongs to the same function sub level concerning the chassis. A number of criteria based on the customer needs were set up and the comparison between the current solution and the generated alternatives started. The result was gathered in a Pugh Matrix, see a section of this matrix in Table 7, complete version can be seen in Appendix C.

The results from the following Pugh matrixes can be interpreted according to: minus sign means that the solution is estimated to be a worse alternative than the current solution, plus sign means better than the current solution. Zero means that the solution alternative is estimated to be more or less as good as the current solution.

Table 7. Pugh matrix round one of the function combination "Cover parts (CP)" and "Hold parts (HP)". Complete version can be seen in Appendix C.

Pugh Matrix, Round 1	**Current Solution**				
Criteria	**CP2+HP11**	**CP1+HP1**	**CP1+HP2**	**CP3+HP11**	**CP3+HP12**
Low cost (D)	0	-	-	-	-
Low volume (R)	0	+	+	+	+
Low weight (R)	0	+	+	+	0
Easy to manufacture (R)	0	0	0	0	0
Easy to assemble (R)	0	-	-	-	-
Low number of components (D)	0	+	+	0	0
Repeatability (R)	0	-	-	-	-
Serviceability (D)	0	-	-	-	-
Sum of all positive (+)	0	3	3	2	1
Sum of all minutes (-)	0	4	4	4	4
Total Score	0	-1	-1	-2	-3
Rank	3	4	4	5	6
Decision/ Further Development:	Y	Y	Y	N	N

Round one of the Pugh matrix for CP and HP resulted in further evaluation for 16 combinations out of 36 possible. The combinations that were ranked 5-8 were eliminated while the ones ranked 1-4 were best ranked and proceeded to the second round with Pugh matrix. In the second round the current solution is switched to a reference solution, which also was the solution with best total score from round one. A section of the result from the second round is gathered in Table 8 below, complete version is found in Appendix D.

Table 8. Pugh matrix round two of the function combination "Cover parts (CP)" and "Hold parts (HP)". Complete version can be seen in Appendix D.

Pugh Matrix, Round 2	**Reference Solution**				
Criteria	**CP2+HP1**	**CP1+HP1**	**CP1+HP2**	**CP3+HP2**	**CP3+HP7**
Low cost (D)	0	-	-	-	-
Low volume (R)	0	0	0	0	0
Low weight (R)	0	0	0	0	0
Easy to manufacture (R)	0	0	0	-	-
Easy to assemble (R)	0	-	-	0	0
Low number of components (D)	0	0	0	0	0
Repeatability (R)	0	-	-	0	0
Serviceability (D)	0	-	-	-	-
Sum of all positive (+)	0	0	0	0	0
Sum of all minutes (-)	0	4	4	3	3
Total Score	0	-4	-4	-3	-3
Rank	1	5	5	4	4
Decision/ Further Development:	Y	N	N	N	N

Round two of the Pugh matrix for CP and HP resulted in further evaluation for 9 combinations out of the 16 proceeded from first round. The combinations ranked 4-5 were worst ranked and therefore eliminated while rank 1-3 proceeded to the next step of the evaluation. The next step concerns total concept combinations, however it was decided to not consider the function "Transport energy" (TE) in this step, since the two existing solutions were estimated to be very similar and were distinguished only from each other when properties like shape and the routing flexibility were investigated. However, it was seen to not affect the result in a larger matter, therefore they were excluded from the evaluation. A section of the result from the Pugh matrix performed for the total concept combinations is visualised in Table 9 below, complete version can be found in Appendix D.

Table 9. Pugh matrix of total concept alternatives. Complete version can be seen in Appendix D.

Pugh Matrix, Total Concepts	**Current Solution**			
Criteria	**CP2+HP11+HC1**	**CP1+HP6+HC1**	**CP2+HP11+HC2**	**CP2+HP11+HC3**
Low cost (D)	0	-	-	0
Low volume (R)	0	+	+	0
Low weight (R)	0	+	0	0
Easy to manufacture (R)	0	0	0	0
Easy to assemble (R)	0	-	-	0
Low number of components (D)	0	+	+	0
Repeatability (R)	0	-	-	0
Serviceability (D)	0	-	-	0
Sum of all positive (+)	0	3	2	0
Sum of all minutes (-)	0	4	4	0
Total Score	0	-1	-2	0
Rank	2	3	4	2
Decision/Further Development:	Y	N	N	Y

The Pugh matrix for the total concept combinations resulted in further evaluation for 17 out of 27. Combinations with rank 1-2 proceeded while rank 3-5 were eliminated.

The proceeded 17 concept combinations were further evaluated in a Kesselring matrix. The same criteria as used in the Pugh matrix were used in the Kesselring matrix, though, the criteria were weighted according importance. High number means, highly important, low number means less important. The weights are listed in the second column in Table 10 below. The weights are then multiple with scoring value and the total score can be calculated. The scoring values that were used in the Kesselring evaluation are displayed in Table 10 below.

Table 10. Scoring values for the Kesselring matrixes' evaluation.

Cost	
Value	Grade
Very high	1
High	2
Acceptable	3
Low	4
Very low	5

Volume	
Value	Grade
Very high	1
High	2
Acceptable	3
Low	4
Very low	5

Weight	
Value	Grade
Very high	1
High	2
Acceptable	3
Low	4
Very low	5

Manufacturability	
Value	Grade
Very low	1
Low	2
Acceptable	3
High	4
Very high	5

Ease of Assembly	
Value	Grade
Very low	1
Low	2
Acceptable	3
High	4
Very high	5

Number of components	
Value	Grade
Very high	1
High	2
Acceptable	3
Low	4
Very low	5

Repeatability	
Value	Grade
Very low	1
Low	2
Acceptable	3
High	4
Very high	5

Servicability	
Value	Grade
Very low	1
Low	2
Acceptable	3
High	4
Very high	5

A section of the results from the Kesselring matric is visualised in Table 11 below, complete version can be found in Appendix E.

Table 11. Kesselring Matrix of total solutions. Complete version in Appendix E.

Kesselring Matrix							
		Ideal		**CP2+HP11+HC1**		**CP2+HP11+HC3**	
Criteria	**Weight**	**Value**	**Total**	**Value**	**Total**	**Value**	**Total**
Low cost (D)	3	5	15	4	12	4	12
Low volume (R)	2	5	10	4	8	4	8
Low weight (R)	3	5	15	3	9	3	9
Easy to manufacture (R)	2	5	10	3	6	3	6
Easy to assemble (R)	2	5	10	4	8	3	6
Low number of components (D)	1	5	5	3	3	3	3
Repeatability (R)	3	5	15	5	15	5	15
Serviceability (D)	2	5	10	5	10	5	10
Sum		90		71		69	
Sum/Sum max		1		0,789		0,767	
Rank				3		4	
Decision/Further Development:				Y		Y	

From the Kesselring it was decided to proceed with 5 out of the 17 proceeded from the total Pugh matrix. These five solutions were the five best scoring solutions and had a sum/sum max ratio above 0.75. The proceeded concept combination solutions are listed and displayed in Table 12 below. All the solutions have CP2 as a solution for the function “Cover Parts (CP)” which is a hard structure cover. Otherwise the combinations have small differences concerning the sub solutions for “Hold Parts (HP)” and “Hold inside connections (HC)”.

Table 12. Concept combination matrix showing the winning total concepts.

Sub- function		1	2	3	4	8	11
Hold Parts	HP						
					Stripes	Food box lid (Snap/clips)/ Eccentric lock	Screw
Cover Parts	CP						
			Hard structure cover (Plastic, Honeycomb, Metal)				
Hold inside conncections	HC						
		Screw		Pressing screw			
Transport energy	TE						
		Solid cable/ Solid busbar	Stranded cable/ Flexible busbar/ Laminal busbar				

CP2+HP4+HC1
CP2+HP8+HC1
CP2+HP8+HC3
CP2+HP11+HC1
CP2+HP11+HC3

Below the winning total concepts are short presented with comments about the opportunities and potential problems:

- **Concept CP2+HP4+HC1:** Hard structure case which holds the parts with stripes and the connections with screws. Stripes is a simple solution that has potential to be faster to assembly than screws. However, it might be hard to mount the stripe in the same way every cycle and therefore the repeatability is low. Another drawback is that they might need to be destroyed and replaced at service. To use screws as fasteners for the connections is a proven method, which enables a defined moment, thus good galvanic contact properties.

- **Concept CP2+HP8+HC1:** Hard structure case which holds the parts with an eccentric lock or clips and the connections with screws. The eccentric lock alternative might not be the best solution when it comes to hold the parts inside the hard case, however it was seen as an interesting solution to hold the case parts together e.g. lid and base case. It has the benefit of being easy to assemble and service. The clips alternative is easy to mount, however it might be easy to destroy the clips during assembly and service.

- **Concept CP2+HP8+HC3:** Similar with the previous concept, the only difference is the fastener for the inner connections. It is a proven method when cables are used, might not be preferable to use if busbars are used. Assembling might be more complex since the cable need to be placed at the correct distance and it might be hard to see due to the fastener holder.

- **Concept CP2+HP11+HC1:** This concept represents the current solution or at least it is similar to how these forms of constructions commonly are designed. It has the benefit of having the same assembly technique for both the fastening for the parts and the connections. If the dimensions of the screws are the same, the concept also has the potential to be assembled with the same tool.

- **Concept CP2+HP11+HC3:** Similar with the previous concept, the only difference is the fastener for the inner connections. The same issues as mentioned for concept CP2+HP8+HC3 above.

All these concept combinations were seen as possible solutions and they were further considered in the system-level-design and detail design phases, see Section 4.3 and 4.4.

4.2.3 Generated Concepts of Sub-Solutions

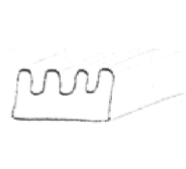
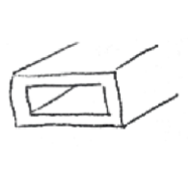
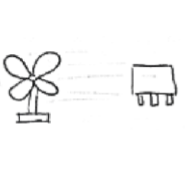
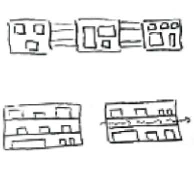
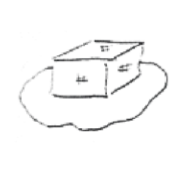
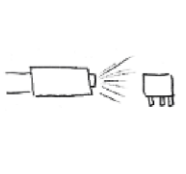
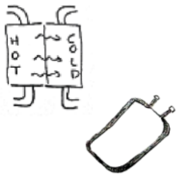
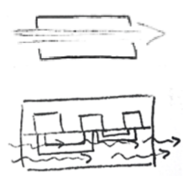
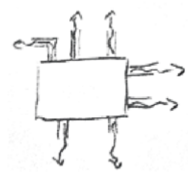
Large amounts of waste heat are a commonly occurring issue in electronics, especially in high current applications. There are numerous ways to cool down electronics, the approaches vary in degree of complexity. Cooling electronics by air or fluid systems are the most common solutions. (Noelle, 2017)

The heat issue was not highlighted as a main problem in the beginning of this project, much due to the robustness of the components in the BDU. However, during the project did Volvo find out that the BDU's heat did cause uneven temperature within the battery pack. This diversity in temperature could affect the battery pack's performance and life span. Without much time to spare, a concept generation cycle to reduce heat in the BDU was added to the project's agenda. The main reason for this was to deliver a concept proposal that did consider as many aspects as possible to be able to present a mature and feasible concept.

Due to the BDU's position, it is not easy to remove the heat produced inside the BDU and from the waste heat from the battery pack. The unit is placed in an area where it is surrounded by stationary air. One solution could be to direct air in to the surrounding volume and cool down the BDU with that air. Although if it was possible to get cold air in there, another problem would occur. The requirements on resistance against moister and dirt makes it impossible to implement a passing airflow through the BDU. This demands a cooling that is indirect like a heat exchanger or similar that can extract the heat from the components to the airflow without having direct contact between them.

With this problem and its boundary conditions in mind, several concepts were generated through a brainstorming session. Further these concepts entered a second brainstorming and screening process with engineers from VCC. The brainstorming sessions ended up in 12 concept alternatives that are visualised in Table 13 below.

Table 13. Result from concept generation session of the heat problem, for clarification see Appendix G and Section 4.2.4.

A	B	C	D	E	F
					
Heatsink	Cable (busbar) with integrated cooling channel in the center	Cooling fan	Split BDU in sections or floors, heated volume is divided	Cooling media	Coating
G	**H**	**I**	**J**	**K**	**L**
					
Cooling media is sprayed onto the components	Heat exchanger/ Cooling plate	Separate airflow	Large conductive area (busbar)	Heat transfer through outgoing wires/cables	Placement of hot components, heat is spread

4.2.4 Evaluated Concepts of Sub-Solutions

The 12 concept alternatives were further discussed to get feedback on their strengths and weaknesses together with comments on whether to keep the concepts, combine them or remove them.

To summarise the gathered feedback and in order to perform a controlled screening, an elimination matrix was created, see Table 14. The same rules in order to interpret the matrix are valid here as in the previous elimination matrix performed in section 4.2.1. Only the concepts involving no N proceeded to the next stage.

Table 14. Elimination matrix of heat solutions. Complete version is found in Appendix F.

Elimination matrix for: Heat				
Criteria fulfilment	**A**	**B**	**K**	**L**
Solves main problem	?	Y	?	?
Fulfils all standards	Y	?	Y	Y
Realizable/Compatible	Y	Y	Y	Y
Resonable cost	Y	N	N	Y
Safe/failsafe	Y	N	?	Y
Enough resources/information	Y	N	N	Y
Low volume/weight	Y	Y	N	?
Sum of all (Y)	6	3	2	5
Sum of all (N)	0	3	3	1
Sum of all (?)	1	1	2	1
Total Score	6	0	-1	4
Comments/ Pros & Cons:	**Pros:** Easy to implement Proven method **Cons:** Airflow is required otherwise it might not work	**Pros:** Effective cooling **Cons:** Complex Expensive Cooling medium can not be conductive Requires circulation	**Pros:** Simple solution **Cons:** Difficult to assemble Low efficiency?	**Pros:** Inexpensice/ simple solution **Cons:** Low efficiency? Might require longer/more busbars
Decision / Further Development:	Y	N	N	Y

The concepts that passed the elimination matrix was a mix of concepts that solved different aspects of the cooling. The good thing about these concepts were that they could be combined to one large system. This system became the solution on the heat problem for this BDU-concept. The solution was a mix of the concepts A, C, I, L.

The concepts:

- **Concept A: Heatsink**

  A heatsink is a commonly used product in cooling systems for electronics. The normally homogenous, extruded or machined piece of metal absorbs heat from parts connected to it and releases the heat in to the surroundings. (ABL, 2017)

- **Concept C: Cooling fan**

  The fan creates an airflow that transports away heat from components. The heat transportation could be made more efficient combined with a heatsink.

- **Concept I: Natural airflow / wind draft**

  Natural airflow or wind draft appears when wind passes through an object. It can also be a forced airflow created by traveling in speed through air. Components placed in this airflow will be cooled if the airflow is cooler than the component.

- **Concept L: Heat efficient layout**
  By placing hot parts away from each other or isolate them from each other, the heat exchange is reduced to a minimum in the given space.

The solution (A+C+I+L) is easy to implement, can be implemented at low cost, efficient and proven way to cool down electronics. The problem with getting rid of heat and at the same time avoid moister and dirt entering the product are solved by having a sealed case with heatsinks both on the inside and the outside.

Due to the project's time limit it is not possible to perform tests to evaluate if the solution works in an efficient way or any other evaluations of the system. The way that air would get in to the area around the BDU are also left out in favour of more important aspects of the project. Solving the heat problem is not one of the main objectives in this project and it is more seen as a delighter if a good solution would be found.

4.3 System-Level Design

This section presents the product architecture and involves design for X.

4.3.1 Developed Product Architecture

The goal with the product is to develop a lightweight product with the functions of a BDU. To create a BDU with lower weight than the current solution without changing the main components inside, the material weight need to be reduced. The material weight could be reduced by reducing dimensions, both outer dimensions and material thicknesses or by changing material. To reduce outer dimension the BDU needs to be more compact. This makes the packaging and layout configuration critical to succeed with the set target.

The first step in this stage was to get a good over view of how all inside electrical components were connected to each other. To connect between the different parts, it was decided to go for busbars, since it is an electrical conductor that is common to use when high currents are involved. (Busbar, 2017) Connection schemes were provided by VCC and helped in the mapping of the system. Early in the process it became clear that the positive and negative side could be separated. This meant that no busbars had to overlap each other and the packaging could be done independent on the positive and the negative side. Findings from the competitor analysis showed that the components did not vary in quantity, rather in size depending on what currents the parts are subjected to. This made the size flexibility of the layout more important than the flexibility in number of components.

The first layouts were 2D-sketches on paper, showing possibilities of different busbar and part configurations. Not all parts were present in these sketches, like the y-capacitors, which has the function of reducing noise, which means reducing electrical disturbance. The reason for this was that they could be placed more easily where space was available. The sketches were also more focused on busbar configuration and the components attached to the busbars. The sketches were used during discussions of pros and cons of the suggested architectures together with people from VCC. An example of these drawings can be seen in Figure 10 below.

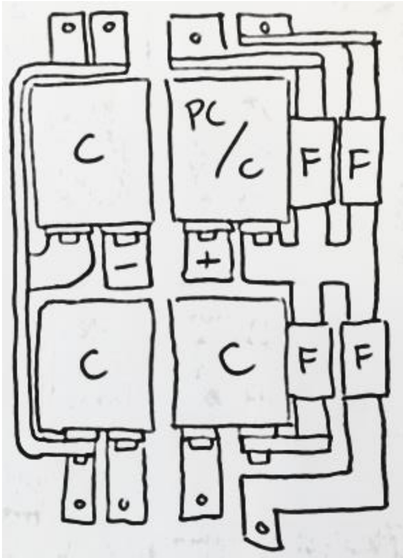


Figure 10. 2D-drawing of an early product architecture concept

After this meeting, changes to the different layouts were made. One of the more critical changes of the packaging were that the main positive and negative contactors should not be facing the same direction due to crash safety. If the contactors are facing the same direction in a crash, they could theoretically both be turned on due to the shockwave from an impact and cause the circuit to close even if the system should be turned off for safety reasons. If they instead are mounted facing different directions, it is more likely that one of the contactors will open the circuit in case of an accident.

Packaging

Packaging have been one of the more important aspects of the product architecture. It is important to keep the volume of the product as small as possible as mentioned earlier to achieve an optimized product in the car industry. Small as possible in this case means, as small as possible without interfering with the ease of assembling or ease of producing the product. A lot of different layouts were tested to investigate how the layout could be optimized.

Clustering by Functions

One approach that was investigated was to cluster the parts with common functions together. All fuses in one area, contactors in another, y-capacitors, etc. This gave advantages regarding serviceability, size and busbar lengths. The problem was that it was not possible to optimize this layout inside the given design area and considering the given restrictions. On the other hand, it was a much smaller and more compact design that would have had more potential in a different design area. Another problem with the clearly separated layout was the EMC. The finding made in the beginning of the project that showed that the positive and negative side could be completely separated was true, but it had a limitation due to EMC. The positive and negative side could still be separated but they needed to be placed close to each other in order to not create an EMC field. This restriction made optimization of the packaging space much harder. A solution to the EMC-problem was to place the negative busbars underneath the positive busbars to keep the tight packaging without having the different busbars far away from each other. This was possible, however it created a new problem, a more complex assembly as can be seen in Figure 11 below.

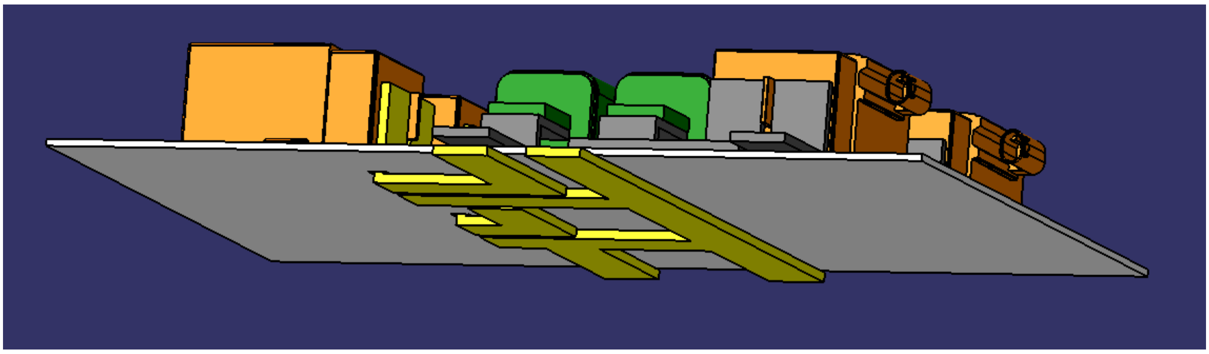


Figure 11. Solution to EMC problem by having positive and negative busbars on top of each other.

Clustering by Geometric Integration and Precision
A new approach was needed and clustering by "geometric integration and precision" (see 3.3.1) was investigated. In this approach, the fix positions of the outer connectors were the starting point for the layout. The other parts did get the position inside the design area best suited for the geometry of that part with short distance between connected pats in mind. This was an iterating process involving moving parts between different locations to create a layout that was as compact as possible. The EMC problem was minimized by putting the positive and negative busbars close to each other, still not overlapping to keep the simplicity for assembly and serviceability. The resulting layout is shown in Figure 12 below.

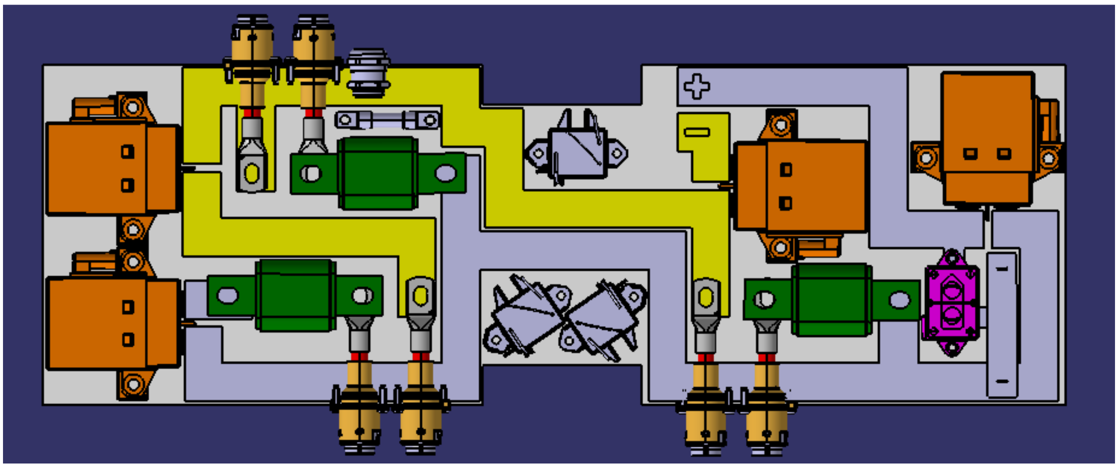


Figure 12. Layout based on clustering by geometric restrictions

Identify the Fundamental and Incidental Interactions
The layouts mentioned above have a lot of interactions between the components. There are mostly electric interactions between the physical connected components. But there are some interactions that are easily missed and those are very important to deal with at this stage.
As mentioned before are heat radiation is a problem that many of the components of the BDU shares with each other. The influence of these incidental interaction has been reduced by spreading the components. EMC-fields are another incidental interaction that does not have a physical connection. This interaction occurs, as mentioned earlier, between electric conductors, in this case, the positive and negative busbars. The EMC gets stronger if the conductors are placed far apart and therefore they have been placed as close as possible to each other without creating too many busbar detours. These are not all interactions between the components,

however, in this project, these are the most critical to consider when designing the product architecture.

4.3.2 Design for X

Design for X have been used as a guide when it comes to trade-offs between different design aspects. The design for X have resulted in a product that are thought through when it comes to assembly and service, as well as it has ensured that the environmental aspects of the design were considered.

Design for Assembly / Serviceability

The BDU have been designed to facilitate assembling by keeping the parts as much as possible in one plane. All the components should be mounted on a base plate. The base plate has a pattern that shows were to mount parts that are in contact with the base. This pattern system is commonly used in 5S workstations to see where tools should be placed and if something is missing on the tool hanger. (Brady, 2011) The goal with this patterns system is to guide the assembly personnel by showing were the parts should be placed and if some parts are missing. If this pattern system works as planned it should not affect the tool cost, but the intention is to lower the cost of quality issues which in total would mean that it is a cost saver.

Design for assembly affected the layout by demanding an easy to access product. No part should demand an assembly in a difficult angle or in tight spaces. All components in the BDU are placed in a way that they can be assembled from above or straight from the sides. The number of different fasteners will be kept as low as possible to reduce different options for the assembly worker. Less possibilities to choose the wrong fastener will improve the quality of the product due to less or very few assembling errors. The scale of economy will also improve with few different parts. The same goes for tools, same fasteners requires the same tool and the tool cost drops when the number of different tools are reduced.

Service operations made to the BDU should, as a requirement, be made through a service hatch underneath the back seat. Due to this requirement, it is crucial that all components that are in risk of breaking can be changed through that service hatch. This puts high demands on the size of the service lids of the BDU. They should be possible to open through the service hatch and big enough to be able to reach most of the components. This problem is solved by having service lids that goes all the way to the edge of the chassis which gives maximum access.

Design for Environment

In this project, there are a lot of parameters that could be taken care off to create a more environmental friendly product. Some are easy to measure like, type of material, weight and type manufacturing process. Others are harder to measure like, energy source, energy consumption and transport. The results of the design for environment are more of a “what should be thought of when designing a BDU” more than a “this are the exact figures in the BDU’s life cycle analysis”.

Low Weight

One thing that people tend to forget when thinking of environmental friendly cars are the weight of the vehicle. The heavier the car is, the more energy it uses during propulsion.
This additional energy consumption could be directly related to higher emissions. This is true both for fully electric cars and hybrid cars if the energy sources are not completely renewable. (Cabrera Serrenho, Norman, & Allwood, 2017)

What does this have to do with the BDU? The BDU is a part of the car that have a mass as all other components. The BDU might not contribute much to the total mass of the vehicle but by making all components just a little bit lighter does a huge difference for the overall weight of the car which in the end saves energy/fuel and thereby lowers the emissions. That is what have been done to the BDU in this project, lower the weight of the product.

Recyclability
The materials chosen for the BDU shall all be recyclable or reusable.
By using fasteners instead of adhesives, it is possible to completely disassemble the BDU to its original parts when recycling them after use.

Environmentally Friendly Production
The BDU should be made by a company in a country that does everything to create as small environmental footprint as possible. This might not be the most cost-efficient way to produce the BDU, but if there should be any extra money spent on the product it should here in order to make sure that the product will be manufactured in a clean way.
A lot of countries and companies are trying to change from environmentally bad energy sources to green sources. The BDU should be produced in a country that cares about the environment and whom are using renewable resources to produce their energy.
New and effective manufacturing processes should be premiered compared to old, dirty and energy consuming processes.

4.4 Detail Design

The detail design section presents the defined part geometries for the BDU, as well as the material and manufacturing selection.

4.4.1 Define Part Geometry

Below each component headline, more details are given about the geometry.

Cover Including Service Lids
The casing has the function of protecting the components inside the BDU from dirt and moister. It should also protect the BDU from being disturb by surrounding EMC-fields, as well as protecting the surrounding environment from the BDU’s EMC-field. The protection of the components is simply done by having a sealed case, the EMC protection is not as easy. The EMC protection demands certain materials and good grounding as mentioned earlier in Chapter 2.

The serviceability is another aspect that have been solved by designing an easy to access casing. The cover is divided in to four parts, the bottom which the circuit board are attached to, the middle lid which forms the cable ditch and closes the gap between the two service lids which are the last two parts of the case except the fasteners and the gasket, see Figure 13.

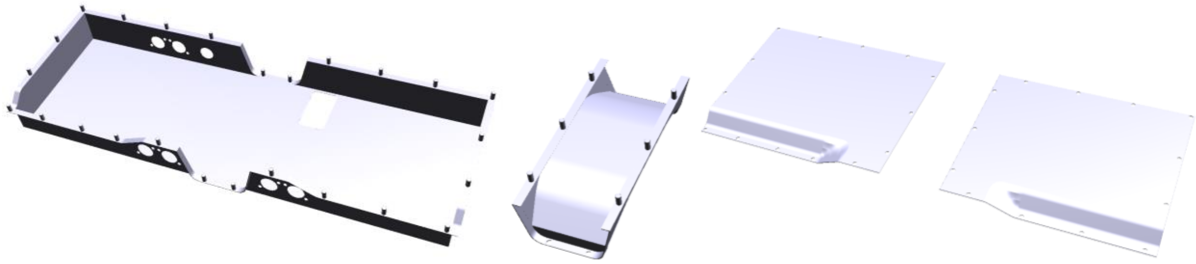


Figure 13. Case parts: Bottom, Middle lid, Service lids

The case is designed with manufacturing in mind. The shapes are open and can be made in one axial manufacturing processes e.g. stamping. It is thereby possible to choose from many commonly used manufacturing processes depending on what best suits the producer. The only part that could have to be going through an after treatment, depending on manufacturing process, are the middle part because of its inward facing flanges, see Figure 14.

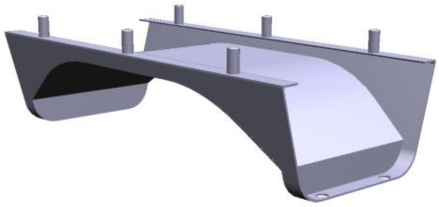


Figure 14. Middle part with flanges

Circuit Board

The circuit board's main task is to work as a non-conductive barrier between the electric components and the metal casing. It should also carry all components and work as a base plate to fix the component against. The design of the circuit board does also help during assembling and disassembling because it has its guiding pattern that shows where to mount the components. For more details about the guiding pattern see Figure 15 below and read more about it in Chapter 4.3.2 "Design for X".

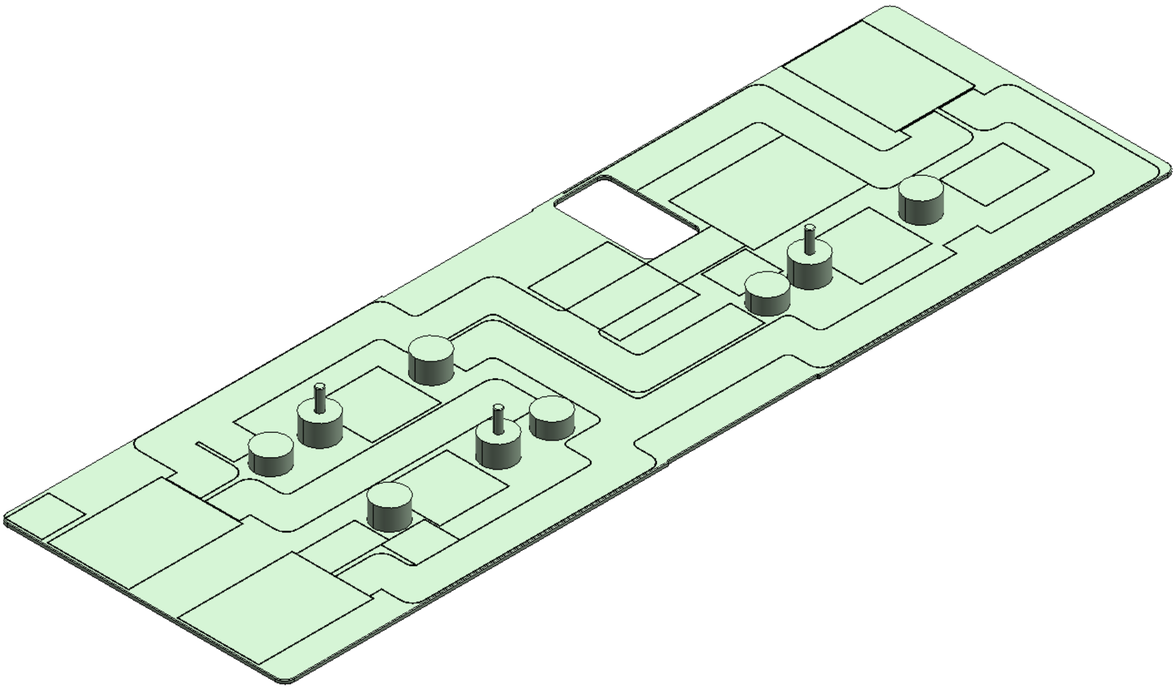


Figure 15. Circuit board with pattern for assembly.

Energy Conductors – Busbars

The busbars main task is to transport energy. When the busbars are made by homogenous metal, as they are in this project, they could also be used as a framework for mounting components on. This design advantage is used together with the circuit board to create a rigid mounting base, see Figure 16.

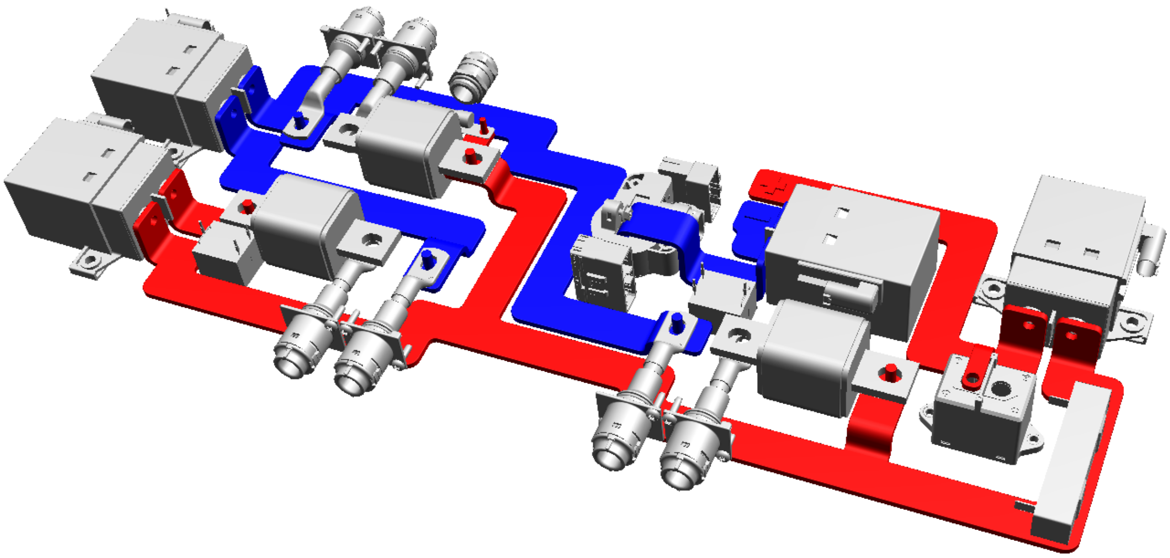


Figure 16. Busbar configuration, blue busbar visualises negative circuit and red, positive.

The busbars are designed to demand as few bending operations as possible. Fewer operations means less complex manufacturing and thereby shorter lead times. The busbars are also designed to be as few as possible. The low number of different busbars gives better scale of economy all through the value chain. All operations could be done by just a cutting machine together with a bending machine. No other machine is needed and that is cost saving.

The strive for easier assembly have created one extra manufacturing operation and that is the attachment of weld studs on to some of the busbars. The weld studs will be used both as fasteners and as guiding pins in the assembly. This is more expensive than creating holes in the busbars but will generate more value in the end due to the much easier assembly.

Contactors
There are four large contactors and one small contactor in the BDU. The small one is a component in the pre-charger circuit. Among the large contactors are two main contactors and two contactors in the high voltage charging circuit.

The main contactors have the function of opening and closing the HV-circuit that supplies the HV-using components with power. One contactor is enough to perform this task but due to the safety standards that VCC has are two contactors used in case of one failing. Another reason why it is advantageously to have two contactors instead of one is the risk of a contactor closing the circuit due to the shockwave created by a collision. This changes the layout of the BDU as well, explained in section 4.3.1. The contactors in the charging circuit has not the same safety requirements as the main contactors because they are not in use during a collision. This means that they can be mounted in the same direction, see Figure 17.

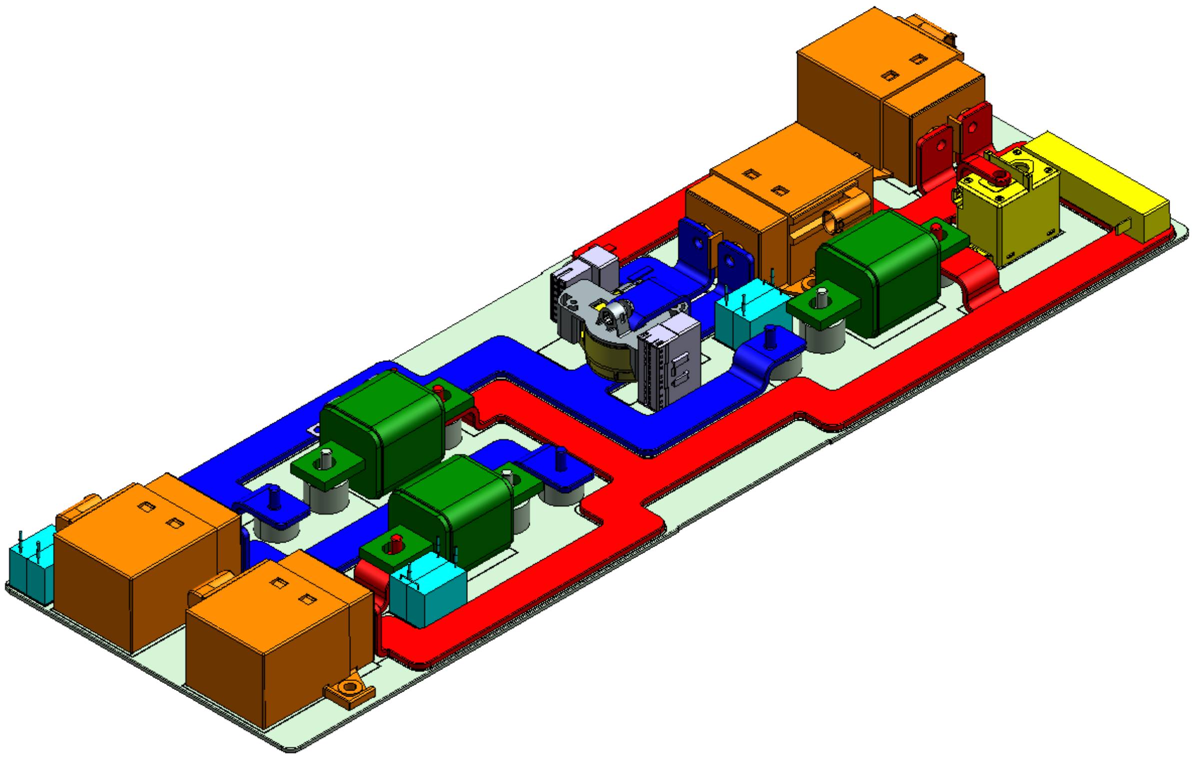


Figure 17. Placement of contactors visualised in orange.

Pre-Charger Circuit
The pre-charger circuit is placed close to the main positive contactor. As mentioned in Chapter 2 is the pre-charger circuit placed there to protect the main contactor from getting damaged by arcing. The pre-charger circuit in this concept consists of one small contactor and a resistance.

The pre-charger acts before the main contactor to get a softer transition between engaged and disengaged circuit.

Gasket
The seal between the bottom of the casing and the three lids are done by using a gasket. But not any gasket. Due to the requirements on EMC is the soft, polymeric gasket covered by a metallic net to ensure conduction between the four parts.

Part and Connection Holders
The reason why all fasteners are nuts combined with weld studs in the same size and not a mix of nuts, bolts and screws are that fewer different parts in a product generates a lot of advantages. The scale of economy is seen all through the value chain.

The space between the fasteners around the lids are maximum 80mm. This is a requirement connected to EMC. To produce quality products that are as identical as possible it is important to be able to verify that all the fasteners are tight enough. This could be done with the nut/stud system.

4.4.2 Material- and Manufacturing Process Selection

To be able to select the most appropriate material and manufacturing process for the cover, circuit board and busbars, a list of constraints was established. The list is shown in Table 15 below, where specific requirements and desires for each component are defined as well as common requirements and desires.

Table 15. Requirements and desires for the material and manufacturing process for the cover, circuit board and busbars.

Constraints / Properties		**Requirement (R) / Desire (D)**
Specific for each component		
Cover	EMC protective (conductive or magnetic)	R
Circuit Board	Non-conductive	R
Busbar	Conductive / Good electric properties	R
In common for the material selections		
Maximum service temp. ≤ 85°C		R
Water resistant		R
Dust resistant		R
Non-flammable		R
Recyclable		D
Low density		D
Low cost		D
In common for the manufacturing processes		
Allow for mass production		R
High quality		R
No need for after treatment		D
Low cost		D

Screening sessions according to the constraints were performed in the software CES and possible alternatives for manufacturing process and material were extracted and further investigated. The action was done for each component and the results of them are presented beneath each component's headline.

Cover

The cover should not just act as dust and water protection, it should also work as shielding for EMI. There are two alternative ways to create a shielding environment, either by using a magnetic material or by using a conductive material(non-magnetic).

From the material screening session performed in CES, two diagrams were set up. One diagram comparing price with density and another one comparing electric resistivity with density, the diagrams can be found in Appendix H. The alternative materials that were extracted from the diagrams were different compositions of aluminium and magnesium. Aluminium is in general less expensive than magnesium, while magnesium is lighter. However, aluminium has lower electric resistivity (more conductive). As mentioned in the Chapter 2 aluminium is an appropriate material that often is used in order to create a shielding enclosure. It was also seen in the benchmark that aluminium often occurs as the choice of material for shielding enclosures. Therefore, a decision was made to choose aluminium instead of magnesium for the cover. One alternative would have been to choose a polymer as the main case and then use a coating that acts as a shielding. However, this alternative was decided to not look further in to, since shielding as coatings only works for higher frequencies. To ensure a full frequency range protection it was therefore decided to use an all metal cover.

In order to manufacture the aluminium case and to meet the process requirements, two processes were selected to be evaluated, sheet hydroforming and stamping. In order to evaluate the processes, a list of relevant information was established, see Table 16 below.

Table 16. Properties gathered for sheet hydroforming and stamping. [2] *(Granta, 2017)*

Properties	**Sheet hydroforming**	**Stamping**
Economic batch size (units)	100-2000	25000-250000
Relative cost index (SEK/ per unit)	90-251	56-68
Production rate (units /h)	10-300	200-2000
Design guidelines	Sheet metal forming process Complex shapes are possible	Constant cross-sectional thickness, shapes with holes tabs, cavities and raised sections are common
After treatment	Further finishing and piercing may be required	
Typical materials	Stainless steels, aluminium, copper	Stainless steels, aluminium, copper
Technical notes	Alternative to traditional stamping techniques Choice of material is important as minimal strain hardening occurs	Complex dies
Typical uses	Automotive, aerospace	Pans, brackets, various mechanical parts
Economics	Saves in tooling costs relative to other stamping processes ~50% less expensive Finishing cost are also commonly lower, does not generally leave scratches and stretch lines Lower scrap rate than traditional processes. Relatively slow cycle time compared to mass production stamping	Fast process Tooling costs are high

For sheet hydroforming, scrap rate and finishing costs are commonly lower, however the cycle time is slow compared to stamping and holes might be required to do afterwards. Both processes are suitable to use for aluminium, although the choice must be more carefully considered for sheet hydro forming since minimal strain hardening occurs. The relative cost index is more exact and lower for stamping. Since the cost was an important parameter according to the requirements, stamping was considered as the most appropriate manufacturing method to recommend for the cover. The different parts of the cover would need different dies. The integrated holes of the cover might need to be manufactured after the stamping operation, if it is not possible to do it in the stamping process, some other process would need to be investigated, some suggestions are laser cutting or electron beam machining, which are two well-known processes that works well with thin sheets.

[2] Economic batch-size: required batch size output before a process becomes competitive.
Relative cost: Estimated values concerning material cost, batch size and capital write-off time.

For the middle part, which forms the cable channel, an additional process is probably required. The flanges of the part need to be bended to the correct angle after the stamping process.

Summarised, the material suggested for the cover was aluminium and the process for the parts require at least two manufacturing processes, stamping and bending, however three processes might be needed in order to make the holes in the parts.

Circuit Board

The circuit board has a simple design, involving few complex features. The only complexities involved is the elevations for the inserts, support features for the busbars and marking pattern for the placement of components. The material of the circuit board requires a non-conductive material in order enable an insulating surface between the conductive components and the cover.

The material screening session performed in CES were decided to only comprise polymer materials, since polymers have good electric insulating properties. Two diagrams were set up. One diagram comparing price with density and another one comparing the yield strength (elastic limit) with density, the diagrams can be found in Appendix H.

The alternative materials that were extracted from the diagrams were different compositions of Polypropylene and Polybutylene (PBT). Generally, PP has lower density than PBT, however PBT has higher elastic limit. Both materials are suitable to use with electronics and the price is more or less the same.

Since weight is an important parameter according to the project objectives, PP was chosen to be a more appropriate material than PBT. The matter of fact that PBT generally has higher yield strength were seen less important, since the part should not be exposed to any higher forces and if needed a special PP could be optimised such as the yield strength could be higher.

Further, an investigation concerning selecting an appropriate manufacturing process for PP started. Two candidates were found, injection moulding and polymer casting. Properties about these processes were gathered and listed and can be seen in Table 17 below.

From the list, it could be extracted that polymer casting is a much slower process than injection moulding, the relative cost is also much higher. Both processes use moulds, which varies in complexity depending on the part complexity. Since price is an important parameter injection moulding seems to be the best candidate and is therefore chosen for the manufacturing of the circuit board. The method also enables to have inserts, however then the cost will increase due to that complexity increasing.

Summarised the suggested material for the circuit board was PP and the part requires one manufacturing process, which was suggested to be injection moulding.

Table 17. Properties gathered for injection moulding and polymer casting. [3] *(Granta, 2017)*

Properties	**Injection moulding**	**Polymer casting**
Economic batch size (units)	10000-1000000	10-1000
Relative cost index (SEK/ per unit)	28-66	151-1310
Production rate (units /h)	60-3000	1-10
Design guidelines	Complex shapes are possible Thick section are not recommended	Complex shapes are possible
After treatment	Quality can be high but may be traded off against production rate	Might be needed.
Typical materials	Thermoplastics	Used for thermosets and some thermoplastics
Technical notes	Generally thin-walled parts Most thermoplastics can be injection moulded	Quality is highly operator-dependent.
Typical uses	Extremely varied, housings, covers etc.	Encapsulations, large gears etc.
Economics	Production rate depends on complexity of component and number of mould cavities Complex moulds Capital and tooling cost are very high Features like screws, inserts may result in increased tooling costs	Complex moulds Tooling cost varies depending on the complexity of the mould.

Busbars

The busbars work as the conductors and therefore they need to be conductive.

In the material screening session, performed in CES, two diagrams were extracted, one comparing the electric resistivity with the price. The second diagram comparing electric resistivity with density. The diagram can be seen in Appendix H.

If the material with lowest electric resistivity (most conductive) would have been selected, that would have been silver, however the price for silver were considered as to high and therefore the material was excluded. The two material candidates that were found were copper and aluminium. Both materials are commonly used as conductors. In general, copper has lower electric resistivity than aluminium. However, copper has much higher density and higher price than aluminium. Although, the electric resistivity was an important parameter and therefore it was decided to choose copper as a material for the conductors.

Several possible manufacturing methods were found for copper, two were selected to be further investigated. These were water jet cutting and laser cutting, information about the processes can be found in Table 18.

[3] Economic batch-size: required batch size output before a process becomes competitive.
Relative cost: Estimated values concerning material cost, batch size and capital write-off time.

Table 18. Properties gathered for water jet cutting and laser cutting, (Granta, 2017)

Properties	**Water jet cutting**	**Laser cutting**
Relative equipment cost	Medium	Very high
Relative tooling cost	Low	Medium
Design guidelines	Leaves high quality edges	Fast and clean process
Typical materials	Can be used to cut almost anything. Particularly good for soft materials.	Precision cutting of metal, ceramic, composite and polymer sheet
Technical notes	Small forces on the workpiece, minimizing need for clamping and damage. Noisy, requires ear protection.	Requires appropriate safety precautions
Typical uses	Cutting food, paper, circuit boards	Circuit boards,
Economics	Competitive process, fast, clean with relatively low equipment and tooling costs.	Expensive equipment, however, process is fast and allows automation

Laser cutting has higher equipment cost and tooling cost compared to water jet cutting. Both processes are clean, fast and are commonly used for cutting in metals. Due to high cost for laser cutting, water jet cutting was considered as the most suitable method to select for the busbars. The busbars require a second operation before they are done, they need to be bent. The most proper choice in this case was to use an ordinary bending machine.

Summarised the busbars are suggested to be made of copper, including two manufacturing processes, a waterjet cutting and a bending operation.

Gasketing

To get proper EMC-shielding it was decided to go for a gasketing solution for the BDU cover. To get a smooth and good sealing properties it was decided to go for a well-known solution, which uses a non-conductive elastomer knitted with a wire mesh made of metal. This form of gasket ensures a continuous contact across the joint which gives a good shield effectiveness, more information about this form of gasketing can be found in the Section 2.3.3.

Fasteners

The fasteners that were chosen were weld studs in combination with nuts. The technique that then can be used is called stud welding. In order to get this combination working together with the BDU case, it is important to consider the boundary conditions of the welding operation. The material choice of the fasteners need to allow a welding operation to the BDU case as well to the busbars. Knowing that the material of the casing is aluminium, it is preferable to choose aluminium for the fasteners also, even though there are techniques that allow welding between aluminium and steel for instance. From that perspective it would also be preferable to use copper for the weld studs attached to the busbars since the material of the busbars was decided to be copper.

4.5 Testing and Refinement

The goal with this project was to generate a concept that could help the further development of the BDU. It should rather be an inspiration and recommendation of improvements areas than a finished product ready for production. This approach affects the level of testing and verification that have been done in this project.

The concept has been redesigned all throughout the project. The iteration has been time consuming but a good way to test and explore new ideas. The design has been changed as soon as new inputs have come in from VCC or when more knowledge of a system has been acquired. Due to this testing of different approaches and following requirements as they change the product have become reality based and in theory functional.

4.5.1 Mechanical Testing

The BDU is placed in a secluded area, between the battery and the underbody of the car, where it does not get exposed to high forces except during a car crash. This gives the opportunity to have a lightweight product with less robust construction.

The forces during a car crash are have not been available in this project and that is why the material dimensions was not computed in FEM simulations or in physical testing which are common approaches. The material thicknesses were instead estimated by investigating other cars parts from VCC to get a feel for the stiffness and sizes.

4.5.2 Geometrical Testing

The possibility to assemble a product is of course extremely important. But just being able to assemble the product is not enough. Making the product easy and efficient to assemble is as important when it comes to large scale production as mentioned in Section 4.3.2. The assembly scheme has been tested in theory and changes have been made to improve the assembly. One of the improvements made during testing are the weld studs that both work as fasteners as well as guiding pins which helps a lot during the assembly process.

Testing have been done by assembling part by part in the CAD program without having clashes between parts or having parts crossing each other. This way of testing feasibility is used by the Propulsion Geometry group at Volvo Cars.

4.5.3 Creepage, Clearance and EMC Testing

The creepage, clearance and EMC have not been prioritised to be simulated and tested further in this project. These properties are a matter of tuning and should not interfere with the overall design of the BDU as it is designed in this project. The creepage and clearance are depending on the distances between parts and the EMC shielding is a matter of tuning the cover for the EMC generated from the parts.

4.6 Final Design

This chapter visualises the final product and explains how well it performs compare to the competitors.

4.6.1 The Design

The final design is shown in the Figure 18-20 below.

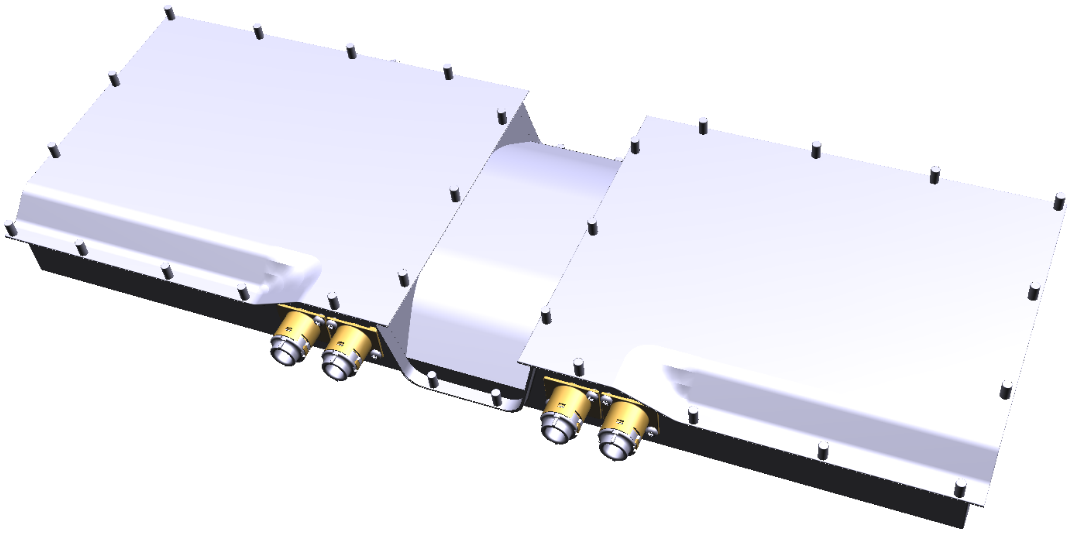


Figure 18. Design of complete BDU

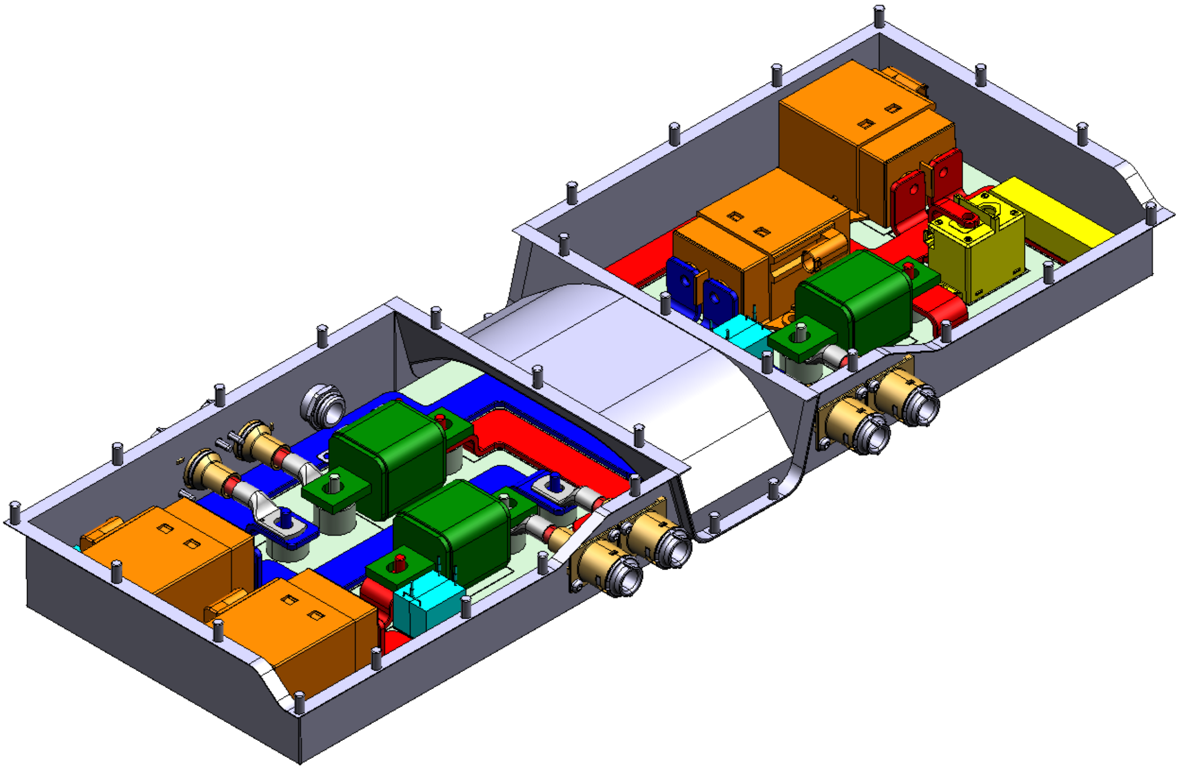


Figure 19. Design of BDU with service lids removed.

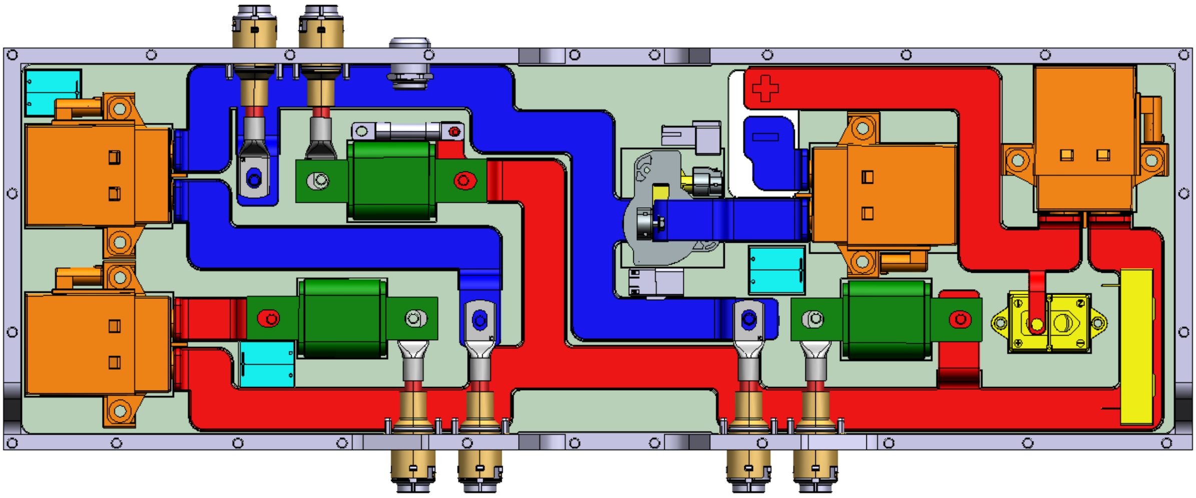


Figure 20.Design of BDU without lids.

4.6.2 Bill of Material

The components in the final concept are presented in Table 19 below. The properties of the parts are specified in quantity, weight and material volume.

Table 19. Bill of material, summary of the component's properties.

	Pcs	Weight (kg)	Total Weight	Volume (m3)	Density (kg/m3)	Material
Bottom case	1	0,63	0,63	0,0002375	2650	Aluminium
Middle lid	1	0,106	0,106	0,00004	2650	Aluminium
Service lids	1	0,373	0,373	0,0001409	2650	Aluminium
Negative Busbars	1	1,014	1,014	0,0001134	8940	Copper
Positive Busbars	1	1,303	1,303	0,0001457	8940	Copper
Base plate	1	0,401	0,401	0,0004428	905	PP
Nuts and washers	60	0,00314	0,1884			Steel
Case studs	31	0,00088	0,02728	8,5E-06	2650	Aluminium
HV Connectors	6					
LV Connectors	1					
Contactors	4					
HV Fuses	3					
LV Fuses	1					
Pre-charger circuit (C+R)	1					
Y-capacitors	3					
Other connections and wiring	-					
Current sensor	1					
Total	117					

The reasons why the table is not complete are that the parts in grey does not warry between the current solutions and the concept solution and that they could give a hint of what type of parts that VCC are planning to use in their upcoming cars.

4.6.3 Comparison Against Competitors

By comparing different aspects, it is possible to see how well this project have succeeded compared to some competitors. The comparison is made between the current concept from

VCC, a concept made by a supplier to VCC and the BDU concept made in this project. The large differences between these concepts are the overall size, busbar volume and the housing volume. The other differences are small and could thereby be neglected.

The figures of the VCC concept and the Project concept are taken from measurements made on CAD-models. To get weight figures have material volumes being multiplied by density of the chosen materials. The figures of the Supplier concept come from the companies own calculations. No CAD-model was available.
The VCC concept are used as a reference and the differences are being presented in percent to avoid revealing any confidential information, see Table 20.

Table 20. Comparison table, showing the difference between the concepts.

	VCC concept	Supplier concept	Project concept
Overall volume	Ref	+0%	-43%
Overall weight	Ref	+11%	-29%
Housing weight	Ref	+36%	-58%
Busbars weight	Ref	-39%	-45%

The green figures show the largest reduction and the red figures shows the worst concept in the different categories.

These figures might look a little bit better than they are in reality. There are several sources of error. One of the more critical sources of error is that all three concepts are concepts and not finished products. This means that dimensions could be or are conceptual and not proven. Many design changes need to be done before any of the BDUs are ready for production.

Even if the figures are based on assumptions, they are implying that they must be extremely incorrect not to end up at the same conclusion as before. The concept made in this project is better compared to the other concepts in these four categories.

4.6.4 Estimated Cost Reduction

The cost calculation of the BDU have a lot of different parameters. Many of these parameters are unknown in this project and the estimated cost will be more of a comparison than a number.

Starting from the beginning with material cost. Material cost can differ a lot depending on quality, supplier, volume, trade agreements, etc. The assumption that can be done is that the material price per kg will be the same as VCC have for other products with similar material specifications. If this assumption is correct, then cost can be directly connected to material weight which mean that the project concept with lower weight have lower material cost than its competitors.

Manufacturing is another cost saving post for the project concept. The competitors BDUs are made from die casting which is, in general, a more expensive manufacturing process than stamping according to CES (Granta, 2017). The prices differ likely between companies and countries.

The assembly time and cost are very hard to predict. The project concept has some assembly advantages, but more investigation is needed to know how much it affects the cost. The cost difference is probably small and can be neglected. The same goes for the cost of service.

Having few different parts does save cost in several areas by the economy of scale. All the way from purchasing, through the logistical flow, assembly to service. The project concept has few different parts and should be more cost efficient than its competitors.

The cost of the components and other common parts in the BDUs are a big post of the total cost of the products but does not differ much between the different concepts and does not contribute to any cost advantage for any of the BDUs.

4.6.5 Fulfilment of Customer Needs

One goal of the project has been to satisfy as many customer needs as possible. Some of the customer needs are vaguer than other and are thereby harder to evaluate if they are fulfilled or not. A summary of the fulfilment of the customer needs can be seen below in Table 21.

Table 21. Summary of fulfilment of customer needs.

Customer Needs	**Requirement (R) / Desire (D)**	**Fulfilled**
1. Lower volume than the current solution	R	Yes
2. Low cost	D	Yes
3. Lower weight than current solution	R	Yes
4. Low heat transfer	D	No
5. Easy to service	D	Yes
6. Easy to manufacture	R	Yes
7. Easy to assemble	R	Yes
8. Environmental friendly	D	Yes
9. Low number of components	D	Yes
10. Higher grade of modularity/ Flexible design	D	-
11. Meet legislations and standards regarding electrified cars	R	Yes

The volume has been reduced and validated by measuring the CAD-model. The volume reduction was a requirement from the customer. The reduction in outer dimensions combined with less material in the housing as well as keeping the same inner components as the current solution does mean that the weight has been reduced as well. As mentioned in the estimated cost chapter above, have the cost likely been reduced as well.

The ease of assembly, manufacturability and the serviceability have been improved in many aspects which can be read about in Section 4.3.2

The heat transfer has been touched upon but not fully solved yet, read more about it in Section 4.2.4.

The environmental aspects have been though of all through the project, and been taken care of in many aspects, but have not been analyse with a life cycle analysis.
The number of components have been kept as low as possible to still meet requirements when it comes to measurable repeatable fastening torque, isolation, and serviceability to mention a

few aspects. All parts that could be combined have been combined. As an example are the busbars combined to only seven separate parts connecting all HV-components.

Legislations and standard have been followed by using requirements set by VCC. The areas which are uncertain if the project have followed set standards in are the ones which needs simulations and calculations like creepage and clearance.

The demand for modularity and flexibility was not as strong customer need as first interpreted. Modularity and flexibility are not a need if the variety of the product is low. In that case it is better to optimize for weight and volume which have been done in this project.

The goal of satisfying the customer needs have been more or less completed. The aspects that needs more work have been looked at and thought of.

4.6.6 How to Assemble the BDU

The assembly scheme of the BDU are made simple to fit mass production. The BDU is built from bottom up by adding the contactors first on the base plate to get the cornerstones of the BDU in place, then connecting them to the busbars to create the web structure which the rest of the inner components will be attached to. All components are added to the correct place by following the marks on the baseplate which shows the geometry of the part which should go in to that place, see Figure 21. The components are also hold in place by studs at the connections before fastened by nuts. The studs make it possible to fasten all nuts at once instead of having to put the fastening tool down between the operations. These operations could be made in a pre-fabrication station to create a sub-assembly of the BDU electronics.

When all components are in place and bolted tight is it time to fasten the baseplate in the bottom of the shell. This is made by the same principle with studs and nuts and by having a non-conductive baseplate is it possible to separate the high voltage circuit from the conductive shell. Next in line are the outer connectors that must be thread through the shell through bushings before fastening to their inner connections. Most of this work could be done in pre-fabrication stations as the base plate assembly but the finishing connections must be made when the base plate and the bottom shell are placed together. This is as far as the BDU could be assembled before it gets connected to the battery pack, see Figure 20.

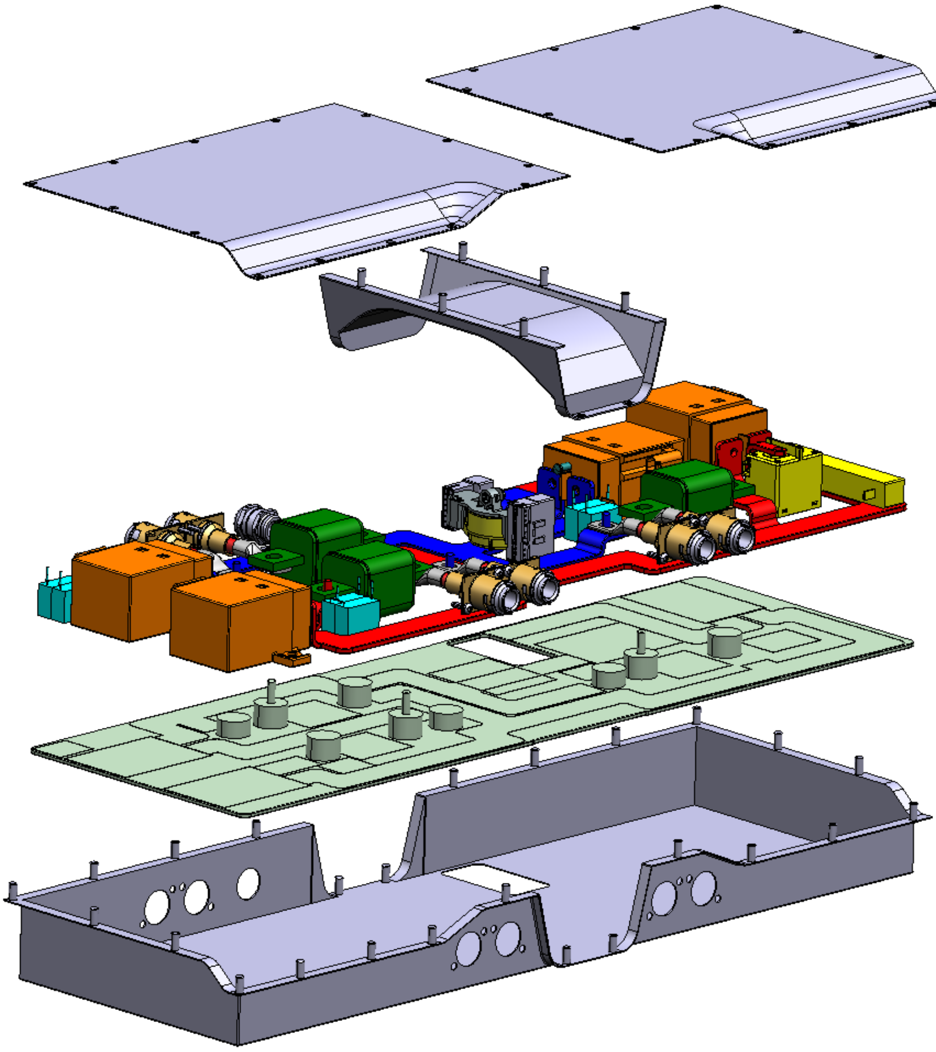


Figure 21. BDU assembled as far as possible before marriage with battery pack.

The connection to the battery pack could and should be made before the marriage to the car body are made in the construction plant. Before placing the BDU on top of the battery pack should some sealing rings be attached around the holes that connects the BDU and battery pack to make sure it stays totally sealed. Then is the BDU fasten by bolts onto the battery pack before connecting the main positive and negative busbars to the battery pack. This is the most dangerous moment of the assembly where for the first time the BDU gets in contact with what could be deadly currents. If everything is as it supposed to, should the connection of the busbars be safe.

Now is the bottom part of the BDU in place and it is time to put on the lids. Starting with adding the conductive sealing followed by the middle part/lid. This lid gets tighten before adding the two lids on each side of the middle lid. These lids will also work as service hatches. All lids are place in position by studs before tightening in correct position by nuts. The only thing now remaining is to connect the cables to the HV-users before the BDU is ready for testing and then usage.

5 Discussion

This chapter covers discussions regarding the relevance of the topic, the methodology and its feasibility as well as project outcome.

5.1 Relevance of the Task and its Objectives

Electrification of cars is in today's society is a hot topic in environmental discussions, where its often is mentioned as a potential solution when it comes to reducing the carbon oxide emissions. However, the major challenges with these cars are to create less expensive and more energy dense battery systems. In order to provide longer ranges for the customer, the battery need to be larger, further that requires more space and that generates a higher cost.

In that sense has the topic of this master thesis concerned a highly relevant topic and work tasks. The purpose of this master thesis was to develop a weight/cost optimised product that performs the functions of a BDU. By achieving a BDU with lower cost that requires less space and is lighter, more space, money and weight is available for a larger battery.

Electrical cars have been around for a while now, however there they are far from fully developed and they are constantly new developments concerning this industry and therefore there are also rapid changes. It is important for the car companies to adapt to these changes otherwise it can be hard to be competitive. This can include competitive manufacturing, for instance low emission rates during manufacturing. It is important to include this in the discussion, that the process and the manufacturing is equally important to consider when talking about emissions. It is not only about how much the car is emitting when it is finished and driven. This argument was the background to why one of the main focuses in this project work has been to always have the environment in mind in every decision, in order to not take decisions that end up in high emission rates. This mindset was gathered in the methodology in the Design for Environment section.

5.2 The Methodology

The approach of the project was based on the Ulrich and Eppinger development cycle. The approach worked as a base throughout the project and acted as a guide to keep the development work ongoing. The phases worked well with the task and objectives of the project. The time planned for some phases were too optimistic, e.g. the knowledge acquisition phase, reading and gathering information as well as processing the information took more time than expected. This phase included an iterative process since new information and inputs were given during the project and that required a lot of time to elaborate through. It was stressful to keep the time slots in the project and these were therefore postponed several times, a buffer time was planned in to the schedule from the beginning and this time was fully utilised.

This project work was carried out in parallel with the development of a new BDU made by VCC. Working in parallel has been both good and bad for this master thesis. A lot of discoveries are made during a development cycle and that have affected in that since that the inputs have changed during the project. With a constant change in problem description there are plenty of time that disappears in to non-value adding work. On the other hand, this situation gave more of a real scenario in work experience that created more learning and good experiences of how to handle these types of situations.

The plan was from the beginning to try to make something that was possible for VCC to use in theory. In order to achieve this, it was decided to accept a conscious scope creep during the project. Thereby it was accepted to follow the changes in the problem description and also to change focus. However, a concern regarding how to know when to stop changing focus came up in order to get the thesis done in time. This was balanced out and development of some sub functions like the heat problem, which arrived late in the process, was only briefly touched upon to be able to finish in time. Probably, it would have been preferable to decide a date from the start of the project concerning a freezing point of demands and input. Which means after this date no new data or demands will affect the project, that would have helped in the planning and to follow the time plan, however the product might not be as competitive as it could have been.

5.3 The Result

In this section, the results have been discussed concerning the design and its feasibility and possibilities of improvements etc. There is also a discussion regarding the fulfilment of needs.

5.3.1 The Design of the BDU

The BDU-concept made in this project shows that it is possible to create a smaller and lighter product than the current concept that indicates a lower cost. With a smaller volume of air comes problem with aspects like heat. The heat problem can be solved with cooling systems, however that requires a more complex product. There could be many different reasons to why the VCC concept was quite large and why it was kept large. It could have to do with the fast change in the electrification of the car industry. Space is always a shortcoming in cars and if there is any space available it is soon filled with products from other design areas. The people developing the BDU gets a design area which they should keep the BDU inside. It is hard to know what size of components that will be demanded. It could also be a safety precaution to make sure that the product will fit in the end. However, the volume could, as shown by the project concept, be less than it is today, but it might then affect the heat properties.

Another reason to why the volumes of the VCC concept and the project concept differs could be that the project should have got more inputs regarding requirements than was received. These inputs might have played a big role and could therefore have influenced the design of the project concept a lot.

One of the bigger learnings during this project have been that a product like the BDU are much more complex than it first seems to be. The design of the BDU have become larger ever since the first design concept was created. As more and more knowledge about the system and the product was retrieved the more the size of the BDU grew. There are a lot of legislations and rules in the car industry and the electrical systems are not an exception. Many of these rules demands a certain design or geometry that have been contributing to the effect of increasing the size of the BDU.

5.3.2 Fulfilment of Customer Needs

The customer needs were stated from VCC due to legislations and wanted performance. These needs were, in high grade, satisfied along with other customer needs that was more of delighters, for instance low number of components.

Some of the customer needs needed testing in order to be evaluate if they were fulfilled or not, only some evaluations were executed. The results would have been more precise if more aspects would have been tested. But by comparing the project's BDU design with the suggested design from VCC and the design from their suppliers, could conclusions be drawn that indicates that the design is feasible according to the customer needs. The part dimensions and the material choices are two examples of parameters that could be seen as feasible checked by referring to the choices made by VCC, their suppliers and other competitors. This way of doing feasibility checks by comparing to other products are not satisfyingly accurate for a product that should go in to production but for a concept it gives a good indication that the product should work with some adjustments.

6 Conclusion

This master thesis has comprised a development work concerning developing a HV-disconnection, commonly known as the product BDU. An investigation regarding the product has been performed in order to investigate issues and opportunities. It was decided to have a main focus on cost and weight optimisation. However, other important aspects were also investigated, such as serviceability, design for assembly and design for environment.

The development work followed a proven development work process. The work was divided in to six main phases, where the first phase concerned finding more information about the BDU, its system, composition and design parameters.

A benchmark was performed and generated a lot of valuable information about different competitors and their approaches for achieving a HV-disconnection. It was found that the approaches differ a lot between the different car manufacturers and also within the Volvo brand. From the benchmark, several opportunities were found regarding weight and cost reduction as well as packaging space.

In order to get a better overview of the BDU, the functions of it was defined. This model was then used as a basis in the concept development phase. The main function that was defined for the BDU was to disconnect battery from the HV-system. Further, concept generation, scoring and screening sessions were performed for some of the sub-functions. From these sessions, five total solutions were generated concerning casing, fastening of components and connections, as well as electrical transporters (conductors). A session was also performed in order to solve a heat problem, some potential ideas were extracted, though more information and research was needed in order to know the feasibility of them. It was decided to leave this problem at this stage due to lack of time.

In the system level design phase, the ideas proceeded from the concept development phase, were further investigated and structuring of the components were performed. The next phase involved the detail design where the part geometries were defined as well as material and manufacturing processes. The case was designed in thin sheet aluminium, with two service lids. The busbars were decided to be made of copper due to its good electrical properties. The circuit board needed an insulating material and therefore a plastic material was seen as the most appropriate choice. The part geometries are designed with manufacturing in mind e.g. the shapes of the casing are open and enable axial manufacturing processes, e.g. stamping. The plastic circuit board has a guiding pattern which gives a benefit during assembly and service, it is easy to understand where to mount and it lowers is also the risk for errors.

The testing and refinement phase were not performed completely due to lack of time, however the plan from the beginning was to verify parameters such as creepage, clearance, packaging in car, assembly test and FEM calculation. The inner packaging and assembly simulations was done in CAD, which was a good check to prove that the design was working in theory. Testing and verification of the other properties would have generated useful information to further optimize the BDU. This phase should have been prioritised higher if the aim for the final product was to have a production ready BDU and not a concept.

The final design is a conceptual design including components that fulfils the functions of a BDU. The final design shows an improved design regarding weight, volume and overall cost, compared to the VCC concept and the supplier concept. The number of different parts is also lower for the project's concept, which indicates that assembly cost might be lower. Manufacturing and material choices have been carefully made, which enabled lower manufacturing costs and material costs.

The final result shows that is possible to reduce the overall weight with 29% and the overall volume with 43%. This rather large weight reduction together with smart manufacturing features, such as the circuit board, generates more value to the product without adding cost. Putting resources and time in early phases of a project normally adds cost which could be a stopper for this kind of activity. Smart changes to the product that improves manufacturability saves cost in the long perspective and should thereby be prioritised even if it could be costly during a short period of time. This project had focus on the early phases of a project to find solutions that could cut costs in the long term.

The customer needs have been more or less fulfilled even if the verification process of them could have been more in depth. A rough estimation often gives a good indication to what the result might be.

The topic of this master thesis work is seen as highly relevant, the topic has concerned some of the challenges that the car industry is facing today. The upcoming challenges of the future are more or less the same, but it involves even more work concerning reduction of volume, weight and cost, since the needs strive for cars with more power that still are environmental friendly.

7 Further Recommendations

In further recommendations are aspects brought up that have not been analyse in this project due to various reasons and thoughts of what can be done to create a better BDU.

7.1 Product Development Recommendations

7.1.1 Position of the BDU

Investigate another positioning of the BDU to create a more optimised BDU. It could be a good idea to first optimise the product's geometry and then find a space that are as close to the geometry as possible instead of choosing the space first and develop the product to fit that geometry.

Integrating the BDU in to the battery pack might save some weight due to that the EMC case could be shared with the rest of the battery as well as the cooling system. Many of the cars benchmarked in this project have this setup. This demands a service hatch in the battery pack to enable service operations in the BDU without having to remove the battery pack.

7.1.2 Design of the BDU

The problem with heat due to a reduced casing volume and shorter distance between parts are not yet analysed. It could be a stopper for the size reduction but could also be a trigger to investigate if a cooling system could be implemented due to the many benefits with having a smaller BDU.
Investigating the possibility of implementing some kind of cooling for the BDU, as many other HV-components already have, is a good way to reduce the space needed for the BDU in the car or be able to have larger components without having a larger BDU.

7.1.3 Material and Manufacturing Process

Replacing copper with aluminium as busbar material would save weight and cost. The problem with aluminium is that it is not as good conductor as copper and thereby need to have a larger cross section area to perform as good as copper, but not by much. The positive sides of aluminium versus copper are the weight that is half of the copper's weight and that is it generally less expensive, as mentioned in section 4.4.2.

The possibility to have a varying cross section area of the busbars should be investigated to create a lighter and cheaper product. Maybe not all components need to have equally wide busbars to function properly.

Investigating if any benefits could be found by using a plastic shell with some kind of coating or additive instead of using a casing in metal with maintained EMC protection. When it comes to curvy shaped parts it is easier and cheaper to use plastic. This will, if needed, give the designer more freedom to adapt the BDU to its surroundings.

7.1.4 EMC Shielding

It is, as mentioned in Section 2.2.3, important to have a sealed casing with all casing parts connected to each other to create an EMC-shield. The concept design, as it is constructed in this project, have a polymeric sealing surrounded by a metal net to both get a connected and sealed case. There are also weld studs with short distance between them around the edges of the case which gives good connection between the lids and the bottom. The connection might be so good that one of these connections could be taken away.

One solution is to keep the studs as they are and change the gasket to a normal polymeric gasket without metal surrounding to have a cheaper gasket. The other solution is to keep the gasket as it is but remove some of the studs to get a lighter and easier to assemble construction. If any of these solutions are possible it should be investigated which one that are the best.

7.1.5 CAE and Testing

The system need verification and tuning. A structural analysis must be performed with the impact forces of a car crash to dimension the parts of the BDU. This kind of analysis is out of the scope for this project. Flow and thermos analyses are other factors that could have impact on the final design of the BDU. These were also seen as out of scope for this project.

To get optimal EMC shielding with low weight, the BDU should be tested in a rig or CAE simulated to tune the lid to gasket connection as well as the thickness of the case. Other electric phenomena like creepage and clearance that affects the geometry should be tuned in together with experts to get the optimal geometry and then tested.

7.2 Upcoming Needs

What upcoming needs have been seen that would influence how the BDU of the future will be designed? What are the challenges of tomorrow?

7.2.1 The Future of Electric Car Charging and the Influence on the BDU

Batteries are still the largest problem when it comes to range and charging time. But as more and more of the large car manufacturers starting to create electrical hybrids and pure electrical cars the knowledge about batteries and the size of the charging infrastructure starts to grow. As an example, have the two large German car manufacturers BMW and Mercedes Benz recently begun a collaboration to create a grid of fast charging stations around Germany trough a company called Chargepoint. The stations should be able to deliver 400kw DC-current which is higher than any current car battery can handle at the moment, but some upcoming EV´s are expected to be able to handle this kind of power. (Lambert, 2017)

As a comparison to the Chargepoint charging stations, the most powerful charging stations that exists today are the Tesla Superchargers and they deliver 145kw.
There are plenty of other similar collaborations between companies to create a grid of charging stations for the upcoming future of electrical cars. (Lambert, 2016)

How does these faster charging stations affect the BDU? Higher currents demand larger cables, connections and components which takes more space. The current placement of the BDU comes with tight restrictions on available space. Larger components could mean that the BDU might have to move or other changes in the geometry might be necessary. To reduce the development work and time needed is it advantageous to have a layout that is scalable or in other ways modular so that the design could be reused.

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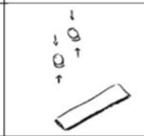
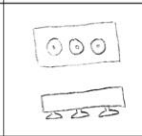
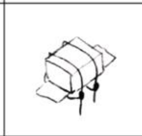
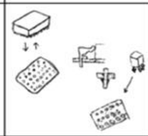
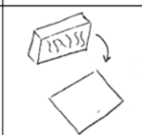
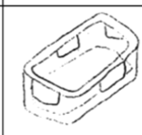
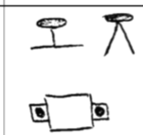
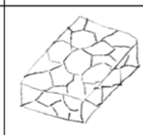
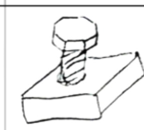
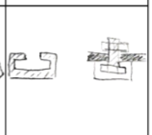
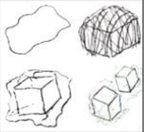
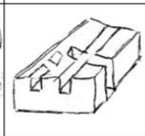
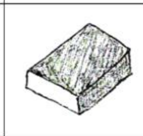
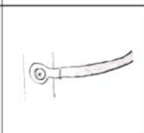
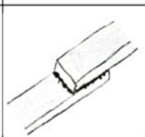
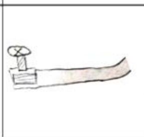
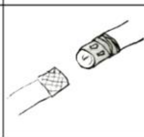
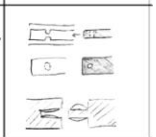
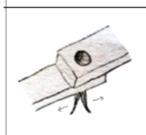
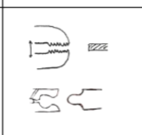
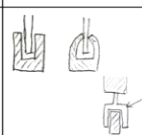
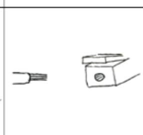
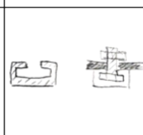
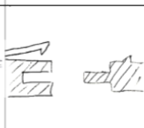
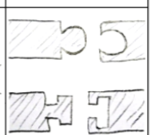
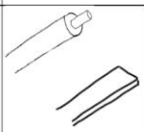
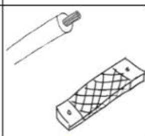
Appendices

Appendix A. Product Specification List

Nr.	Product specification list	R/D
	Legalislations	
1	The product shall be designed to meet international and VCC legislations, requirments and standards	**R**
	Service and After market	
2	Components inside the BDU shall be exchangeable without disassembling the battery when removed from the vehicle	**R**
3	Components inside the BDU should be exchangeable without removing the battery from the vehicle	**D**
	Environment	
4	The BDU shall be developed with a "life cycle" approach in order to minimize environmental impact	**R**
5	Number of different materials should be kept as low as possible in order to facilitate future recycling	**R**
6	Materials that are not compatible at recycling should be easy to separate from each other	**D**
7	The BDU shall be designed to withstand normal use trough the vehicle lifetime	**R**
	BDU components	
8	Confidential	**R**
	Contactors	
9	Confidential	**R**
10	Mounting direction on negative and positive contactors shall differ from each other (eliminate risk for reclosing during mechanical acceleration forces)	**R**
	Main contactors	
11	Confidential	**R**
12	Confidential	**R**
13	Confidential	**R**
	DC charging contactors	
14	Confidential	**R**
15	Confidential	**R**
	Pre-charge contactor	
16	Confidential	**R**
17	Confidential	**R**
18	Confidential	**R**
	Fuses	
19	Confidential	**R**
20	Confidential	**R**
21	Confidential	**R**
22	Confidential	**R**
23	Breaking capacity of fuses or other components protecting the system shall be above short circuit peak current of the battery pack.	**R**
24	Confidential	**R**
	Lead-trough connections	
25	Confidential	**R**
26	Confidential	**R**
27	Confidential	**R**
28	Confidential	**R**

	Current meter	
29	The current meter should be placed in the BDU	**D**
	Pre-charge resistor	
30	Confidential	**R**
	Y-capacitors	
31	Y-capacitors shall be installed to reduce noise coming from inverters and DC-charging	**R**
	HV measurement points	
32	The mesurement point should be placed to enable diagnose of fuses and contactors	**R**
33	The measurement points shall be read by the BECM	**R**
	Function environment	
34	All parts of the complete electrical system shall be designed to withstand all environmental factors without intermitted or permanent loss of function	**R**
	Electrical	
35	The BDU should be designed for EMC	**R**
36	Confidential	**R**
	Packaging/ Geometry	
37	Confidential	**D**
38	Confidential	**D**
39	All HV components including wire harness shall be packed in a way to prevent short circuits due to crash	**R**
40	In all crash situations, which not trigger the SRS system, the mechanical and electrical integrety of all HV components shall be intact	**R**
	Influence on surronding systems	
41	External heating of the battery cells shall be kept to a minimum.	**R**
	Economics	
42	Confidential	**R**

Appendix B. Concept Combination Table of Total Solutions

Sub- function		1	2	3	4	5	6	7	8	9	10	11	12
Hold Parts	HP												
		Velcro (under or over)	Magnet	Suctions cups	Stripes	Lego/Battleships/Arduino	Nothing	Glue/Tape	Food box lid (Snap/clips)	Bending clips	Formable net	Screw	Mounting rail
Cover Parts	CP												
		Flexible/Film cover (Vacuum bag, thin film, tape wrap, melt glue, silicone, rubber)	Hard structure cover (Plasic, Honeycomb, Metal)	Coating cover									
Hold inside conncections	HC												
		Screw	Soldering/Glueing	Pressing screw	Cable screw/twist (Coaxial)	Bulb click / Banana Plug	Bending clips	"Welding tongs" / Clothingpin	Pressed/Clamped/ Busbar sadle	Spring loaded holder (Audio cable connection / Spinlock)	Mounting rail	Snap lock connection	Puzzle (With cover to lock)
Transport energy	TE												
		Solid cable/ Solid busbar	Stranded cable/ Flexible busbar/ Laminal busbar										

Appendix C. Elimination Matrix of Total Solutions

Elimination matrix for HC:						**Alternative Solutions**						
Criteria fulfilment	**HC1**	**HC2**	**HC3**	**HC4**	**HC5**	**HC6**	**HC7**	**HC8**	**HC9**	**HC10**	**HC11**	**HC12**
Solves main problem	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Fulfils all standards	Y	Y	Y	Y	?	?	?	?	?	Y	Y	?
Realizable/Compatible	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	?	Y
Reasonable cost	Y	Y	Y	N	N	Y	N	?	N	?	N	N
Safe/failsafe	Y	Y	Y	Y	Y	N	Y	?	?	Y	Y	?
Enough resources/information	Y	Y	Y	Y	Y	?	Y	Y	Y	Y	Y	Y
Low volume/weight	Y	Y	Y	N	Y	Y	N	N	N	N	Y	?
Sum of all Yes (Y)	7	7	7	5	5	4	4	3	3	5	5	3
Sum of all No (N)	0	0	0	2	1	1	2	1	2	1	1	1
Sum of all "more info is needed" (?)	0	0	0	0	1	2	1	3	2	1	1	3
Total Score	7	7	7	3	4	3	2	2	1	4	4	2
Comments/ Pros & Cons:	**Pros:** Simple & proven solution Serviceability **Cons:** High assembly time	**Pros:** Simple & proven solution **Cons:** High assembly time Serviceability	**Pros:** Simple & proven solution Serviceability **Cons:** High assembly time	**Pros:** Lock-property Serviceability **Cons:** Expensive, Space requiring	**Pros:** Short assembly time **Cons:** Manufacturability Complex Expensive	**Pros:** Simple solution, Few parts Short assembly time **Cons:** Unsure contact properties	**Pros:** Serviceability Short assembly time **Cons:** Risk of slip Expensive Space requiring	**Pros:** Simple solution Few parts **Cons:** Risk of slip Serviceability	**Pros:** Known principle **Cons:** Expensive, Risk of slip Manufacturability	**Pros:** Adaptable mounting position Simple solution **Cons:** Many parts High weight Expensive Space requiring	**Pros:** Smart lock function Known principle **Cons:** Expensive Complex solution Manufacturability	**Pros:** Short assembly time Serviceability **Cons:** Unsure volume of lock mechanism Unsure contact properties
Decision / Further Development:	Y	Y	Y	N	N	N	N	N	N	N	N	N

Appendix D. Pugh Matrices of Total Solutions

Round 1.

Pugh Matrix, Round 1	Current Solution						
Criteria	**CP2+HP11**	**CP1+HP1**	**CP1+HP2**	**CP1+HP3**	**CP1+HP4**	**CP1+HP5**	**CP1+HP6**
Low cost (D)	0	-	-	-	-	-	-
Low volume (R)	0	+	+	0	+	0	+
Low weight (R)	0	+	+	0	+	0	+
Easy to manufacture (R)	0	0	0	0	0	-	0
Easy to assemble (R)	0	-	-	-	-	-	-
Low number of components (D)	0	+	+	0	0	-	+
Repeatability (R)	0	-	-	-	-	-	-
Serviceability (D)	0	-	-	-	-	-	-
Sum of all positive (+)	0	3	3	0	2	0	3
Sum of all minutes (-)	0	4	4	4	4	6	4
Total Score	0	-1	-1	-4	-2	-6	-1
Rank	3	4	4	7	5	8	4
Decision/ Further Development:	Y	Y	Y	N	N	N	Y

CP1+HP7	**CP1+HP8**	**CP1+HP9**	**CP1+HP10**	**CP1+HP11**	**CP1+HP12**	**CP2+HP1**	**CP2+HP2**	**CP2+HP3**	**CP2+HP4**
-	-	-	-	-	-	0	0	-	0
+	+	+	0	+	0	+	+	-	0
+	+	+	0	+	0	+	+	0	+
0	-	0	-	0	-	+	+	0	0
-	-	-	-	-	-	-	-	+	+
+	0	0	+	0	-	+	+	0	0
-	0	-	-	0	-	-	-	-	-
-	-	-	-	-	-	0	0	0	0
3	2	2	1	2	0	4	4	1	2
4	4	4	5	3	6	2	2	3	1
-1	-2	-2	-4	-1	-6	2	2	-2	1
4	5	5	7	4	8	1	1	5	2
Y	N	N	N	Y	N	Y	Y	N	Y

CP2+HP5	**CP2+HP6**	**CP2+HP7**	**CP2+HP8**	**CP2+HP9**	**CP2+HP10**	**CP2+HP12**	**CP3+HP1**	**CP3+HP2**	**CP3+HP3**
-	-	0	0	0	-	-	-	-	-
0	0	+	0	0	0	-	+	+	+
0	0	+	0	0	0	-	+	+	+
-	-	+	-	0	0	-	0	0	0
0	+	-	+	0	-	0	-	-	-
-	+	+	0	0	+	-	+	+	0
0	0	-	0	-	-	-	-	-	-
0	+	-	0	0	-	0	-	-	-
0	3	4	1	0	1	0	3	3	2
3	2	3	1	1	4	6	4	4	4
-3	1	1	0	-1	-3	-6	-1	-1	-2
6	2	2	3	4	6	8	4	4	5
N	Y	Y	Y	Y	N	N	Y	Y	N

CP3+HP4	CP3+HP5	CP3+HP6	CP3+HP7	CP3+HP8	CP3+HP9	CP3+HP10	CP3+HP11	CP3+HP12
-	-	x	-	-	-	-	-	-
+	+	x	+	+	+	+	+	+
+	+	x	+	+	+	+	+	0
0	0	x	0	0	0	0	0	0
-	-	x	-	-	-	-	-	-
0	0	x	+	0	0	0	0	0
-	-	x	-	-	-	-	-	-
-	-	x	-	-	-	-	-	-
2	2	x	3	2	2	2	2	1
4	4	x	4	4	4	4	4	4
-2	-2	x	-1	-2	-2	-2	-2	-3
5	5	X	4	5	5	5	5	6
N	N	N	Y	N	N	N	N	N

Round 2.

Pugh Matrix, Round 2	**Reference Solution**					
Criteria	**CP2+HP1**	**CP1+HP1**	**CP1+HP2**	**CP1+HP6**	**CP1+HP7**	**CP1+HP11**
Low cost (D)	0	-	-	-	-	-
Low volume (R)	0	0	0	0	0	0
Low weight (R)	0	0	0	+	0	-
Easy to manufacture (R)	0	0	0	0	0	-
Easy to assemble (R)	0	-	-	-	-	0
Low number of components (D)	0	0	0	+	0	0
Repeatability (R)	0	-	-	-	-	0
Serviceability (D)	0	-	-	-	-	-
Sum of all positive (+)	0	0	0	2	0	0
Sum of all minutes (-)	0	4	4	4	4	4
Total Score	0	-4	-4	-2	-4	-4
Rank	1	5	5	3	5	5
Decision/ Further Development:	Y	N	N	Y	N	N

CP2+HP2	**CP2+HP4**	**CP2+HP6**	**CP2+HP7**	**CP2+HP8**	**CP2+HP9**	**CP2+HP11**	**CP3+HP1**	**CP3+HP2**	**CP3+HP7**
0	0	-	0	0	0	0	-	-	-
0	-	-	0	-	-	-	0	0	0
0	0	-	0	-	0	-	0	0	0
0	0	-	0	-	-	-	-	-	-
0	+	+	0	+	+	+	0	0	0
0	0	+	0	0	-	-	0	0	0
0	0	0	0	+	0	+	0	0	0
0	0	+	-	0	0	0	-	-	-
0	1	3	0	2	1	2	0	0	0
0	1	4	1	3	3	4	3	3	3
0	0	-1	-1	-1	-2	-2	-3	-3	-3
1	1	2	2	2	3	3	4	4	4
Y	Y	Y	Y	Y	Y	Y	N	N	N

Pugh Matrix, Total Concepts

Pugh Matrix, Total Concepts	Current Solution			
Criteria	**CP2+HP11+HC1**	**CP1+HP6+HC1**	**CP1+HP6+HC2**	**CP1+HP6+HC3**
Low cost (D)	0	-	-	-
Low volume (R)	0	+	+	+
Low weight (R)	0	+	+	+
Easy to manufacture (R)	0	0	0	0
Easy to assemble (R)	0	-	-	-
Low number of components (D)	0	+	+	+
Repeatability (R)	0	-	-	-
Serviceability (D)	0	-	-	-
Sum of all positive (+)	0	3	3	3
Sum of all minutes (-)	0	4	4	4
Total Score	0	-1	-1	-1
Rank	2	3	3	3
Decision/Further Development:	Y	N	N	N

Criteria	CP2+HP1+HC1	CP2+HP1+HC2	CP2+HP1+HC3	CP2+HP2+HC1	CP2+HP2+HC2	CP2+HP2+HC3
Low cost (D)	0	-	0	0	-	0
Low volume (R)	0	+	0	0	+	0
Low weight (R)	+	+	+	+	+	+
Easy to manufacture (R)	+	+	+	+	+	+
Easy to assemble (R)	-	-	-	-	-	-
Low number of components (D)	+	+	+	+	+	+
Repeatability (R)	-	-	-	-	-	-
Serviceability (D)	0	-	0	0	-	0
Sum of all positive (+)	3	4	3	3	4	3
Sum of all minutes (-)	2	4	2	2	4	2
Total Score	1	0	1	1	0	1
Rank	1	2	1	1	2	1
Decision/Further Development:	Y	Y	Y	Y	Y	Y

Criteria	CP2+HP4+HC1	CP2+HP4+HC2	CP2+HP4+HC3	CP2+HP6+HC1	CP2+HP6+HC2	CP2+HP6+HC3
Low cost (D)	0	-	0	-	-	-
Low volume (R)	0	+	0	0	+	0
Low weight (R)	+	+	+	0	0	0
Easy to manufacture (R)	0	0	0	-	-	-
Easy to assemble (R)	+	-	+	+	-	+
Low number of components (D)	0	+	0	+	+	+
Repeatability (R)	-	-	-	0	-	0
Serviceability (D)	0	-	0	+	-	+
Sum of all positive (+)	2	3	2	3	2	3
Sum of all minutes (-)	1	4	1	2	5	2
Total Score	1	-1	1	1	-3	1
Rank	1	3	1	1	5	1
Decision/Further Development:	Y	N	Y	Y	N	Y

CP2+HP7+HC1	CP2+HP7+HC2	CP2+HP7+HC3	CP2+HP8+HC1	CP2+HP8+HC2	CP2+HP8+HC3
0	-	0	0	-	0
+	+	+	0	+	0
+	+	+	0	0	0
+	+	+	-	-	-
-	-	-	+	-	+
+	+	+	0	+	0
-	-	-	0	-	0
-	-	-	0	-	0
4	4	4	1	2	1
3	4	3	1	5	1
1	0	1	0	-3	0
1	2	1	2	5	2
Y	Y	Y	Y	N	Y

CP2+HP9+HC1	CP2+HP9+HC2	CP2+HP9+HC3	CP2+HP11+HC2	CP2+HP11+HC3
0	-	0	-	0
0	+	0	+	0
0	0	0	0	0
0	0	0	0	0
0	-	0	-	0
0	+	0	+	0
-	-	-	-	0
0	-	0	-	0
0	2	0	2	0
1	4	1	4	0
-1	-2	-1	-2	0
3	4	3	4	2
N	N	N	N	Y

Appendix E. Kesselring Matrix of Total Solutions

Kesselring Matrix									
		Ideal		CP2+HP1+HC1		CP2+HP1+HC2		CP2+HP1+HC3	
Criteria	Weight	Value	Total	Value	Total	Value	Total	Value	Total
Low cost (D)	3	5	15	4	12	3	9	4	12
Low volume (R)	2	5	10	4	8	4	8	4	8
Low weight (R)	3	5	15	4	12	4	12	4	12
Easy to manufacture (R)	2	5	10	4	8	4	8	4	8
Easy to assemble (R)	2	5	10	3	6	2	4	2	4
Low number of components (D)	1	5	5	3	3	4	4	3	3
Repeatability (R)	3	5	15	3	9	1	3	3	9
Serviceability (D)	2	5	10	3	6	2	4	3	6
Sum		90		64		52		62	
Sum/Sum max		1		0,711		0,578		0,689	
Rank				8		11		9	
Decision/Further Development:				N		N		N	

CP2+HP2+HC1		CP2+HP2+HC2		CP2+HP2+HC3		CP2+HP4+HC1		CP2+HP4+HC3		CP2+HP6+HC1		CP2+HP6+HC3	
Value	Total	Value	Total	Value	Total	Value	Total	Value	Total	Value	Total	Value	Total
4	12	3	9	4	12	4	12	4	12	3	9	3	9
4	8	4	8	4	8	4	8	4	8	4	8	4	8
4	12	4	12	4	12	4	12	4	12	4	12	4	12
4	8	4	8	4	8	3	6	3	6	3	6	3	6
3	6	2	4	2	4	4	8	3	6	4	8	3	6
3	3	4	4	3	3	3	3	3	3	4	4	4	4
3	9	1	3	3	9	4	12	4	12	4	12	4	12
3	6	2	4	3	6	4	8	4	8	4	8	4	8
64		52		62		69		67		67		65	
0,711		0,578		0,689		0,767		0,744		0,744		0,722	
8		11		9		5		6		6		7	
N		N		N		Y		N		N		N	

CP2+HP7+HC1		CP2+HP7+HC2		CP2+HP7+HC3		CP2+HP8+HC1		CP2+HP8+HC3		CP2+HP11+HC1		CP2+HP11+HC3	
Value	Total	Value	Total	Value	Total	Value	Total	Value	Total	Value	Total	Value	Total
4	12	3	9	4	12	4	12	4	12	4	12	4	12
4	8	4	8	4	8	4	8	4	8	4	8	4	8
4	12	4	12	4	12	4	12	4	12	3	9	3	9
4	8	4	8	4	8	3	6	3	6	3	6	3	6
2	4	1	2	2	4	5	10	4	8	4	8	3	6
4	4	4	4	4	4	4	4	4	4	3	3	3	3
2	6	1	3	2	6	5	15	5	15	5	15	5	15
2	4	1	2	2	4	4	8	4	8	5	10	5	10
58		48		58		75		73		71		69	
0,644		0,533		0,644		0,833		0,811		0,789		0,767	
10		12		10		1		2		3		4	
N		N		N		Y		Y		Y		Y	

Appendix F. Elimination Matrix of Sub-Solutions

Elimination matrix for: Heat	**Alternative Solutions**											
Criteria fulfilment	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
Solves main problem	?	Y	Y	?	Y	?	Y	Y	Y	Y	?	?
Fulfils all standards	Y	?	?	Y	N	?	N	Y	?	Y	Y	Y
Realizable/Compatible	Y	Y	Y	Y	Y	Y	?	Y	?	Y	Y	Y
Resonable cost	Y	N	Y	?	Y	N	N	?	Y	N	N	Y
Safe/failsafe	Y	N	?	Y	N	Y	N	Y	Y	Y	?	Y
Enough resources/information	Y	N	Y	?	N	?	N	Y	Y	Y	N	Y
Low volume/weight	Y	Y	Y	N	?	Y	?	?	Y	N	N	?
Sum of all (Y)	6	3	5	3	3	3	1	5	5	5	2	5
Sum of all (N)	0	3	0	1	3	1	4	0	0	2	3	1
Sum of all (?)	1	1	2	3	1	3	2	2	2	0	2	1
Total Score	6	0	5	2	0	2	-3	5	5	3	-1	4
Comments/ Pros & Cons:	**Pros:** Easy to implement Proven method **Cons:** Airflow is required otherwise it might not work	**Pros:** Effective cooling **Cons:** Complex Expensive Cooling medium can not be conductive Requires circulation	**Pros:** Proven in electrical products **Cons:** Requires electricity Standard regarding moist and dust might be a problem	**Pros:** Easy to implement **Cons:** Might not solve the problem Space requiring	**Pros:** Easy solution **Cons:** Hard to implement and to follow standards	**Pros:** Simple solution **Cons:** Low efficiency?	**Pros:** Effective cooling **Cons:** Complex, expensive, does not fulfill standards	**Pros:** Proven cooling solution **Cons:** Complex Might require much space	**Pros:** Inexpensice/ simple solution Effective in speed **Cons:** Ineffective at standstill Might bring moisture and dirt	**Pros:** Inexpensice/ simple solution **Cons:** Requires much space	**Pros:** Simple solution **Cons:** Difficult to assemble Low efficiency?	**Pros:** Inexpensice/ simple solution **Cons:** Low efficiency? Might require longer/more busbars
Decision / Further Development:	Y	N	Y	N	N	N	N	Y	Y	N	N	Y

Appendix G. Explanation of Concepts, Heat Problem

One solution to the heat problem was to separate the BDU in to several small boxes instead of having one large box. This could reduce the exchange of heat between the components and the heat radiation on the busbars could be reduced as well. The drawbacks with this solution might be longer busbars, larger weight and more complex assembling.

Another solution that came up was to divide the BDU in to different floors. With this solution it could be possible to both isolate the busbars from the heat radiation of the components and maybe arrange a better cooling for the busbars without affecting the components. The assembling could be a little more complicated with this type of solution but that might be all right if it solves the heat issues. It could also be more expensive depending on the construction.

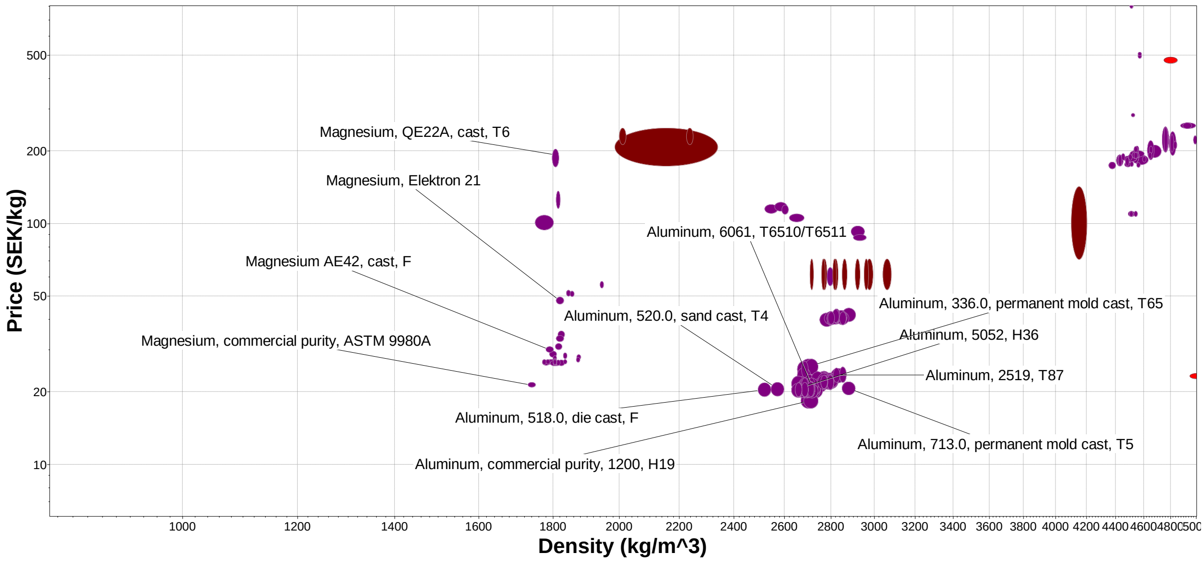
These two concepts were clustered together to form a concept called "Concept D".

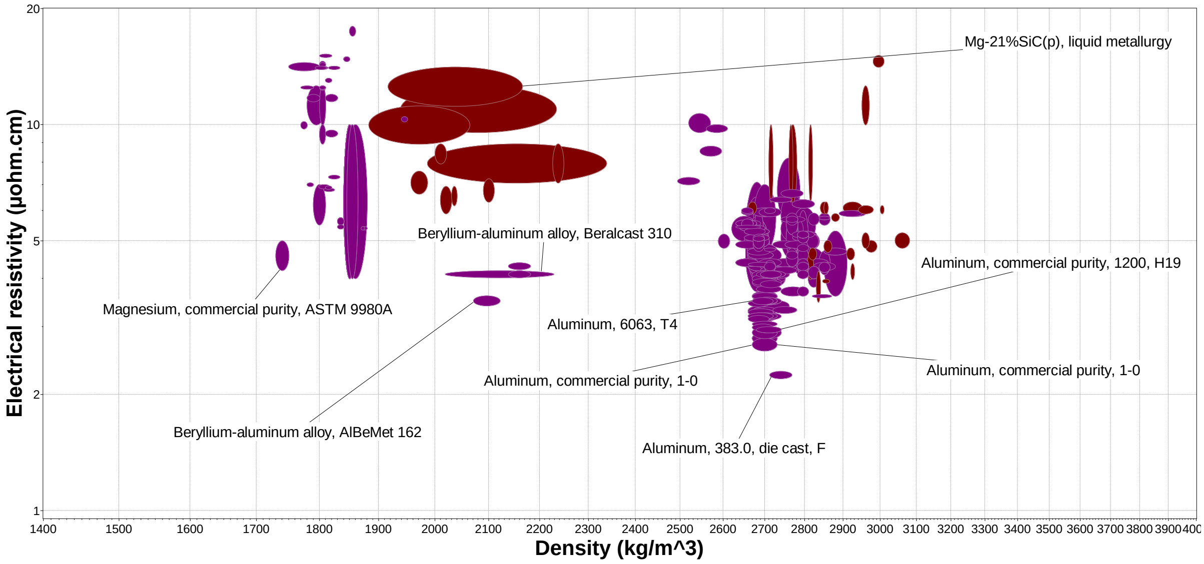
The size of the busbars was also discussed due to the possibility of more area equals more heat dissipation. The area would be even more important when in contact with a cooling plate. How such a change in geometry would affect the electric performance of the busbars have to be investigated if this solution should be used. Cost and space compared to positive effect are another uncertainty with this solution. This concept got the name "Concept J".

Some kind of cooling circuit was discussed as well. The problem with this idea is that the cooling circuit existing in the car are almost maxed out. One solution could be to improve the performance of the existing cooling circuit or add another cooling circuit. This concept became "Concept H".

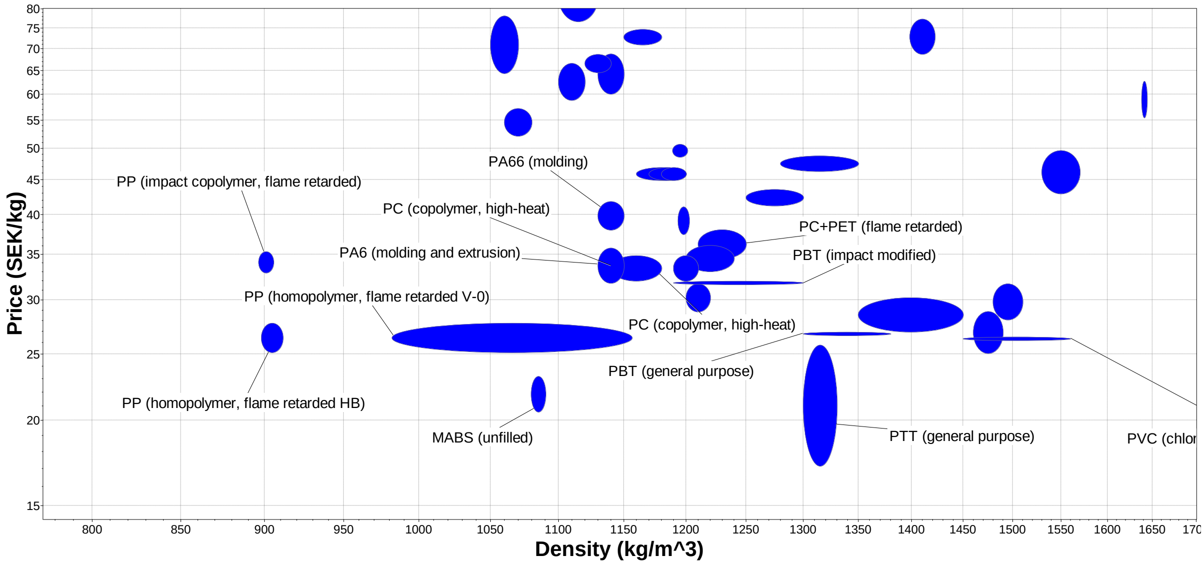
Appendix H. Material Selection Charts

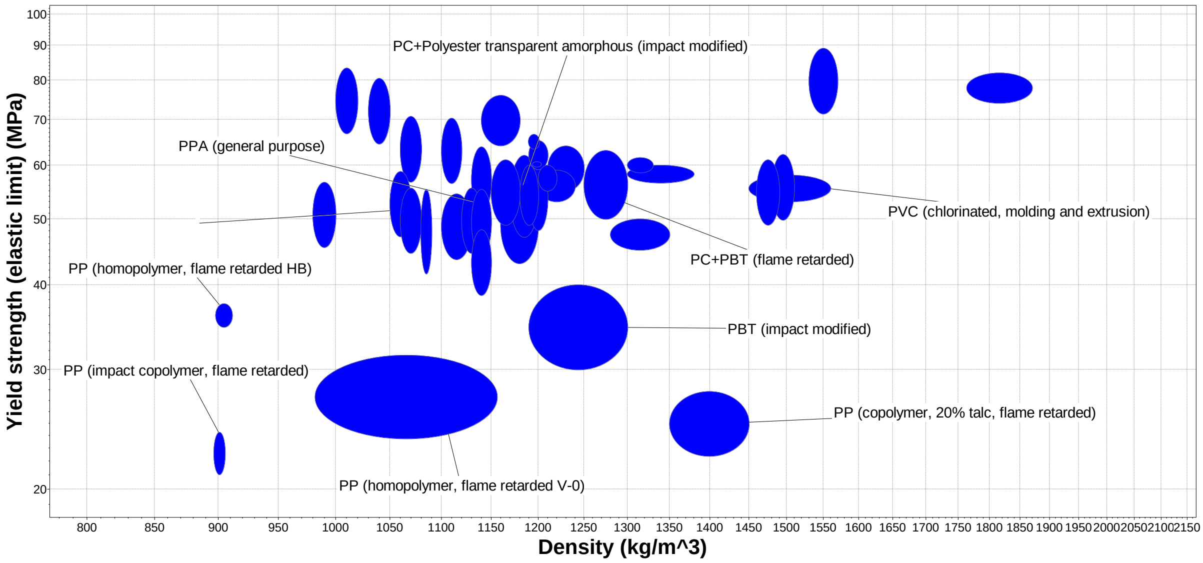
Cover:



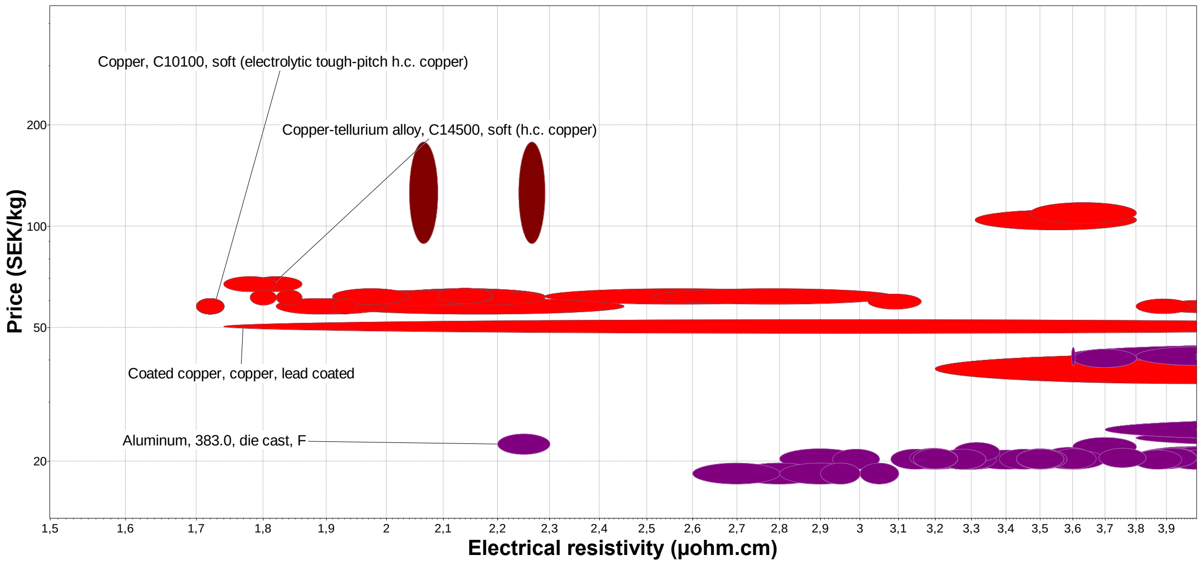


Circuit Board:

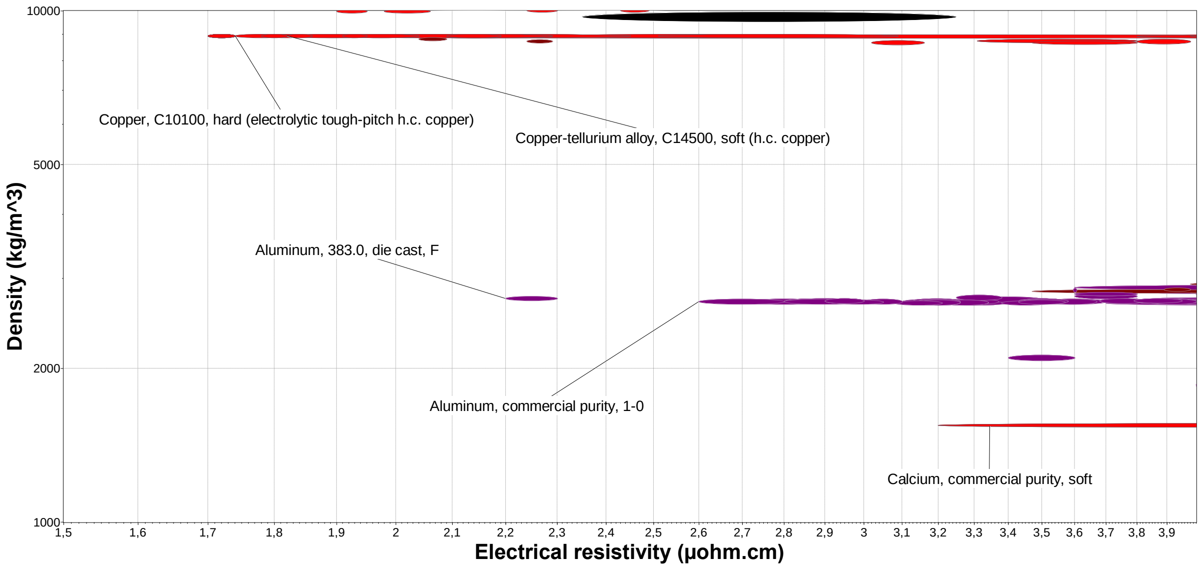




Busbars:



Copper, C10100, soft (electrolytic tough-pitch h.c. copper)
Copper-tellurium alloy, C14500, soft (h.c. copper)
Coated copper, copper, lead coated
Aluminum, 383.0, die cast, F
Price (SEK/kg)
200
100
50
20
1,5
1,6
1,7
1,8
1,9
2
2,1
2,2
2,3
2,4
2,5
2,6
2,7
2,8
2,9
3
3,1
3,2
3,3
3,4
3,5
3,6
3,7
3,8
3,9
Electrical resistivity (µohm.cm)



Copper, C10100, hard (electrolytic tough-pitch h.c. copper)
Copper-tellurium alloy, C14500, soft (h.c. copper)
Aluminum, 383.0, die cast, F
Aluminum, commercial purity, 1-0
Calcium, commercial purity, soft
Density (kg/m^3)
10000
5000
2000
1000
1,5
1,6
1,7
1,8
1,9
2
2,1
2,2
2,3
2,4
2,5
2,6
2,7
2,8
2,9
3
3,1
3,2
3,3
3,4
3,5
3,6
3,7
3,8
3,9
Electrical resistivity (µohm.cm)