CHALMERS
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Development of Wireless Charging Component in Vehicle

Design and Positioning

Master's thesis in Product Development

IDA ANDERSSON
JOSEFIN ODDEBY

Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

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Ida Andersson
Josefin Oddeby

Supervisors: Johan Malmqvist, Chalmers University of Technology
Torbjörn Andersson, Volvo Cars

Examiner: Johan Malmqvist, Chalmers University of Technology

Chalmers University of Technology
Department of Industrial and Materials Science
SE-412 96 Göteborg, Sweden
Telephone +46 (0)31-772 10 00

Cover:
A visualisation of the developed vehicle assembly induction plate positioned in a Volvo car.

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Abstract

Inductive charging, or wireless charging, is an upcoming technology in the automotive industry. A fluctuating magnetic field is created by alternating current in the transmitting coil. This magnetic field then induces current in the receiving coil. In this way, the energy transfer is accomplished wirelessly. The wireless charging system consists of three main parts: wall box, ground assembly and vehicle assembly. The vehicle assembly is the component which is placed in the vehicle and consists of, amongst other parts, the receiving coil. Volvo Cars is currently developing the technology together with suppliers. However, the problem is to find a proper position and geometry of the vehicle assembly component that fits in their electric vehicle platform. In addition, the inductive charging system must not affect the overall performance of the vehicle negatively.

The project initiated with an investigation of the technology to predict the future and possible standards of the system. No standard for positioning was yet established. However, the technology investigation showed a trend of positioning the component in front, under the vehicle. The investigation was followed by a problem decomposition where functions and components necessary for the vehicle assembly were identified. This resulted in a requirement specification. The main phase of the project was the concept development. Several concepts of position and geometry ideas were generated and later evaluated and screened to result in one most promising concept. The final concept was positioned in the front and below the vehicle, on the front sub frame. It was integrated with an existing vehicle component, the on-board charger. The volume needed for the electronics of the vehicle assembly was assumed to be reduced by 40 % due to this integration.

The position of the vehicle assembly was optimal with both the customer and the company in mind. The concept developed was designed to make as few critical modifications on the sub frame as possible. The existing undershield of the car was modified to be used as an aluminium shield to protect surrounding components from magnetic field exposure. The concept was developed using the recommended practise SAE J2954 which ensured an efficient energy transfer. Finally, already existing components in the car were utilised to decrease the volume of the concept together with the overall number of components in the platform.

Keywords: Wireless charging, inductive charging, vehicle assembly, product development

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List of Abbreviations

AC	Alternating Current
BEV	Battery Electric Vehicle
CAD	Computer Aided Design
CMA	Compact Modular Architecture
DC	Direct Current
EMC	Electromagnetic Compatibility
EV	Electric Vehicle
GA	Ground Assembly
HV	High Voltage
ICE	Internal Combustion Engine
LV	Low Voltage
OBC	On-Board Charger
PE	Polyethylene
PMP	Polymethylpentene
PP	Propylene
R&D	Research and Development
SAE	Society of Automotive Engineers
SPA	Scalable Product Architecture
SUV	Sport Utility Vehicle
VA	Vehicle Assembly
WLAN	Wireless Local Area Network
WLC	Wireless Charging
WPT	Wireless Power Transfer

1 Introduction

The report describes a master's thesis project performed at the master programme Product Development at Chalmers University of Technology during the spring semester of 2018. The project was executed in close collaboration with the automotive company Volvo Cars. The project involved designing and positioning of a component for inductive charging of electric vehicles.

In the following, a brief description of the company Volvo Cars and the background of the project being carried out are presented. Also, problem description, aim and objectives, and delimitations are defined. Finally, the structure of the report is explained.

1.1 Volvo Cars

Volvo Cars is a global automotive manufacture company, offering cars in the premium segment. Volvo was first established in 1927 in Gothenburg, Sweden. Up until 1999, Volvo Cars was a part of Volvo Group, when they were sold to Ford Motor Company. Since 2010, Volvo Cars is owned by the Chinese company Zhejiang Geely Holding Group. (Volvo Cars, 2018)

Volvo Cars produces three model series of cars; the 40, 60 and 90 series. Almost each series can be in three different versions: sedans (S), versatile estates (V) and sport utility vehicles (SUV and XC), followed by sub-models such as cross country and extra tall models. The company uses two different platforms for their cars, the Compact Modular Architecture (CMA) platform and the Scalable Product Architecture (SPA) platform. The versions of the 40 series use the CMA platform, while the 60 and 90 series use the SPA platform. Hybrids as well as electric cars will be included in the platforms (Ian, 2016).

In 2017, Volvo Cars sold 571 577 cars worldwide. This is an increase of approximately seven percent compared to 2016. (Volvo Cars, 2018) The company is world leading in the automotive industry and recently won the awards *World Car Awards 2018* for the XC60 and *2018 European Car of the Year* for the XC40. The company focuses on safety and people with their strategy *Designed Around You.*

1.2 Project Background

To be able to maintain Volvo Cars competitive position, they need to develop and integrate more advanced technology in their vehicles. In order to succeed with the implementation of new technology, the packaging space needs to be optimised.

An upcoming technology within the automotive industry is inductive, also called wireless, charging. The car industry develops vehicles which are running on renewable energy. In order to make the charging of electric cars more convenient for their users, one of the next steps is to develop and integrate inductive charging. No cord is needed to be connected to the car when charging the battery. Instead, the induction plate positioned in the car is connected wirelessly by electromagnetic induction to another induction plate component located separate from the vehicle, for instance, in the ground.

At this point, the induction plate is not available in production at Volvo Cars. However, other competitors of Volvo Cars are developing the technology and will presumably release their technology in the near future. Also, some competitors are already offering this technology, but with a lower power input. To be able to keep their competitive position, Volvo Cars has to offer this technology with a high power input to their customers.

1.3 Problem Description

Inductive charging, or wireless charging, is when the induction technology is used to charge devices. Induction is a phenomenon which gives a direct relationship between electric and magnetic fields. The wireless charging is possible due to magnetic fields and coils. The induction plate in the vehicle is exposed to fluctuating magnetic field which in response generates current. The current is, with some modifications, translated to the battery for energy storage.

Volvo Cars is currently developing the technology together with suppliers. However, the problem is to find a proper placement and geometry of the component so that the inductive charging technology will work as expected, without affecting overall performance of the vehicle. Regarding placement, the main focus will be to find a position in the next generation SPA platform of an electric vehicle.

At this point, there is no standard regarding placement of the ground induction plate. Therefore, Volvo Cars has to be flexible and try to predict its specifications if such standards will emerge. To ensure competitiveness when launching the technology, predictions of the future are also needed to understand in which direction the competitors are striving with their technology.

1.4 Aim and Objectives

The aim of the master thesis is to:

Develop and optimise a geometry of a vehicle assembly (VA) induction plate and its positioning in the vehicle that does not affect car performance negatively and allows for ease of manufacturing and assembly.

In other words, to succeed with this master thesis, the intended outcome will be a proposal of the placement and geometry of the induction plate in the vehicle. The proposal could then be up for further development and refinement, and later in the future, be implemented in the new electric Volvo cars. Manufacturing and assembly possibilities will be considered, as well as mechanical properties. The car performance as well as the user experience will be in focus to ensure that neither the car nor the users will be affected negatively. The proposal should be optimised and fit within the updated SPA platform.

To be able to fulfil the aim and also succeed with the project, questions have been stated that will be answered during the project work. The questions are as follows:

- How does inductive charging work?
- Which functions are needed to be included in the VA system?
- Which are the most crucial requirements on the component?
- Where is the optimal position of the technology in the platform?
- How could inductive charging technology be implemented in the platform?
- How could the technology be integrated with existing vehicle components?

1.5 Delimitations

The students writing this thesis are from a mechanical engineering background and have only basic knowledge about electricity and how it works. Some knowledge about the subject had to be acquired to ensure feasibility of the developed concept. However, the development process will be focused on mechanical parts due to the limited knowledge about electricity.

The inductive charging technology mainly consists of three systems, a ground assembly (GA) induction plate positioned for instance on the ground, a VA induction plate in the vehicle, and a wall box connected to a socket. In this project, only the VA will be up for development. The platform that will be used in the development of the induction plate will be the next generation of the SPA platform. The SPA platform is continuously updated. Therefore, if any late updates of the platform will be made which affect the project, the earlier version will be locked and used.

Furthermore, the vehicle type will be a battery electric vehicle (BEV), meaning that the car is only driven by electricity. Hybrid vehicles running partly on electricity will not be investigated in the project. Moreover, the inductive charging technology will only be used when a vehicle is standstill with motor turned off. This means that the inductive charging will take place in the garage or parking lot.

It is important to note that the overall performance of the vehicle must not be changed, meaning that critical components in the vehicle are not allowed to be removed. It could, however, be feasible to move or redesign less critical parts, such as cabling, or parts that could fit somewhere else in the car. In that case, discussions with experts will be held.

The project work will not result in any working physical prototype. The intended outcome will be one proposal that shows the principles of the geometry and placement of the induction plate in the vehicle. This will be a virtual model, designed in a computer aided design (CAD) environment. The proposal is a concept that has to, after the end of this project, be further analysed and developed before possible realisation. Also, due to the time restriction, no tests such as strength calculations or life time tests will be carried out on the concept. However, these aspects will be taken into consideration when developing the component.

1.6 Report Structure

Initially, the report explains the theory needed for understanding the inductive charging technology and the principle of how an electric vehicle works. In the following chapter, the methods for undertaking the work process is described for each part of the development process. This is then followed by a technology and stakeholder analysis. Here, patent and benchmark searches are conducted as well as a prediction of the future for the wireless charging system. In addition, the stakeholders of the project are defined and analysed. Then, in the *problem decomposition* chapter, functions and components needed for the vehicle assembly being developed are identified. This resulted in a requirement specification where all demands and wishes of the vehicle assembly are listed. In the two subsequent chapters, the actual concept development work was carried out. First, the generation, screening and evaluation of position ideas of the vehicle were accomplished. When the placement was determined, ideas of the geometry of the vehicle assembly was generated which later resulted in a final chosen concept. This concept was in the following chapter, *detailed design*, more thoroughly designed, and in *final design*, the concept is presented as well as a fulfilment of the requirement specification. The report is summarised with a *discussion*, *conclusion* and *recommendations for further development*. This is then followed by a reference list, and in the very end of the report, the *appendices* are presented. In the report, the project group is referred to as the students writing the thesis.

2 Theory

The chapter explains the theory needed to understand the development process of a vehicle assembly induction plate. Inductive charging was the main function and technology of the component being developed. Therefore, the chapter will describe the phenomenon, together with an explanation of how the technology could be utilised in a vehicle. Knowledge about restrictions and explanations of the platform of interest was necessary to be able to develop a VA that will be compatible with the platform. Therefore, information about the global coordinate system and ground clearance of the vehicle are described. When it comes to the inductive charging technology, many aspects have to be included. For this purpose, a standard used as a guideline throughout the project is explained in the end of the chapter.

2.1 Electric Vehicle

An electric vehicle (EV) is a vehicle which is propelled by electricity. The electric vehicle could either be exclusively or partially powered by electricity (Cleveland & Morris, 2015), which usually are denoted as battery electric vehicle (BEV) and hybrid electric vehicle (HEV) respectively. In this section, only the BEV and its basic functions will be explained, together with comparison to the traditional internal combustion engine (ICE). Hereinafter, EV is referred to as BEV.

Normally, an electric vehicle uses one or more electric motors to propel the vehicle, compared to the traditional ones using one internal combustion engine. According to Rim and Mi (2017), the electric vehicle was first invented in 1827, compared to the internal combustion engine which was invented in the 1860s. During these years, the electric motor was popular since it was more reliable than the internal combustion engine. However, in the first decades of 1900, major progress of the ICE was made and gasoline became cheaper. As a result of this, the ICE became more attractive for propelling the vehicle and has been so since then. (Larmine & Lowry, 2003) However, in the recent years, the development of electric motors has advanced and again started to compete against the traditional ICE's.

Basically, the components needed to powering an electric vehicle are electric motor, energy storage, power converter and transmission. Also, an electric charger to refuel the energy storage is needed. This electric charger could be a wired charger that has to be plugged in to the vehicle when the battery needs to be charged, or a wireless charger such as inductive charging. (Rim & Mi, 2017) The inductive charging technology will be more thoroughly explained later in this chapter. A component called on-board charger (OBC) is needed to transform the alternating current (AC) from the external power source into direct current (DC) to be able to charge the battery. See Figure 2.1 for a basic layout of an electric vehicle.

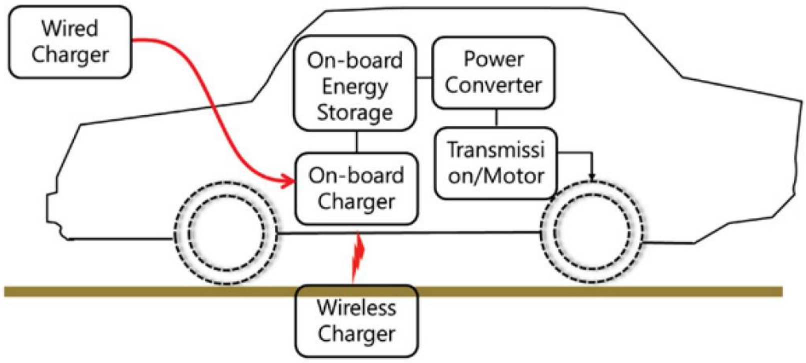


Figure 2.1: Basic layout of an electric vehicle, retrieved from Rim & Mi (2017, Figure 3.1).

In an EV, the electric motor can be a synchronous or asynchronous motor. The two motor types work differently but both consists of two main parts: a stator and a rotor. The rotor is the component that rotates in the motor, while the stator is stationary where the coils are positioned. To the stator, a three phase alternating current is brought. The most significant difference between the two motor types is that the rotor in a synchronous motor consists of strong magnets, while the rotor in an asynchronous does not. Instead, the alternating current creates a magnetic field in the coils which in its turn induces current to the rotor. (Blomhäll, 2017) This phenomenon is called induction and will be explained more thoroughly later in this chapter. The motion created in the rotor is utilised to propel the vehicle.

An electric motor is powerful and robust. The motor speed depends on the frequency of the AC power supply. To be able to change the drive wheel speed, the frequency of the power supply has to alter. An electric motor can work efficiency in any speed range. An internal combustion engine however, will only work efficiently within certain motor speed range, and not in as large range as an electric motor. Therefore, for an ICE, a transmission is needed for alternating the drive speed. A transmission for speed varying is not needed in an EV. (Learn Engineering, 2017)

Due to the linear motion of the pistons in an ICE, this motion has to be transformed into rotational motion. This results in problem regarding mechanical balancing. Many parts are needed in order to solve issues such as balancing problems. This makes an ICE heavy. In an electric motor, direct rotational motion is achieved so no motion converter is needed or additional components for balancing the motor. (Learn Engineering, 2017) Also, an electric motor is much lighter than an ICE. For instance, in a Tesla Model S which is an EV, the motor weighs almost 32 kilograms with a power output of 270 kW. In comparison, a typical ICE weighs approximately 180 kilograms with a power output of 140 kW. (Morris, 2017)

The electric motor is powered by electricity from a battery pack. The battery pack consists of a large number of batteries which nowadays are rechargeable. These batteries are connected to be able to achieve the power required to propel the EV. (Learn Engineering, 2017) Most of the batteries in an EV receive DC power. However, the motor requires AC power. Therefore, the DC from the battery pack has to be transformed into AC before entering the motor, using a power converter. In this case, the power converter is an inverter. (Rim & Mi, 2017) The inverter can also control the AC power frequency. Hence, the inverter also controls the speed of the motor.

A transmission, or gearbox, is connected to the electric motor. The motor speed is reduced by this gearbox before it enters the drive wheel. As explained earlier, an electric motor does not need a speed varying transmission. However, this transmission is only used for speed reduction and torque multiplication. In the transmission, normally a differential is installed. (Learn Engineering, 2017) A differential is used to control the speed on the drive wheels, enabling them to turn with different speeds. This is needed to be able to make a turn. The outer wheel has to rotate faster than the inner wheel for the vehicle to be able to turn. (Brandt, 2018). For the vehicle to be able to driving backwards, in other words, enable the reverse gear, the motor speed just have to turn in the opposite direction. This leads to that the wheels will rotate in the opposite direction and the car will be moving backwards.

The EV’s have the possibility to use regenerative braking. This mechanism uses the kinetic energy to slow down the velocity of the vehicle instead of wasting it in heat which is normally happening when braking the vehicle by the brake pedal. During regenerative braking, the battery can be charged. This occurs when the accelerator pedal is released. The electric motor will during the regenerative braking work as a generator. In this case, the drive wheels drive the motor, or the generator. Electricity is generated which then can be used to charge the battery pack. (Learn Engineering, 2017)

In conclusion, an electric vehicle with rechargeable batteries is needed to be charged. As briefly explained, the charging of the battery pack can be done using, for instance, a cord plugged in to the vehicle or by wireless charging. This wireless charging can be done by using induction. In following sections, the phenomenon induction as well as how the inductive charging in a vehicle works are explained.

2.2 Induction

Induction, or electromagnetic induction, is a phenomenon which gives a direct relationship between electric and magnetic fields (Wolfson, 2011). It was first discovered in the 1830s by Michael Faraday (Allt om Vetenskap, 2007). He performed an experiment using two coils of copper around cores of iron. One of the coils was connected to a battery where electric current could flow through. The other coil was connected to a galvanometer which is an instrument that can measure weak electric current (Magnet Academy, 2014). Thus, this coil was not provided with any current from a power source. When the two coils approached toward each other, the galvanometer indicated a flow of current through the second coil. (Allt om Vetenskap, 2007)

Easily described, electricity can be generated with the help of a fluctuating magnetic field. To be able to achieve induction, an inductor is needed. It is usually a coil which consists of an isolated wire. When a magnet is passing through the coil, electric current is created. This because of the fluctuating magnetic field. If the magnet is not moving in the coil, no current will be produced. (Allt om Vetenskap, 2007)

Also, induction can be produced without using a magnet as explained in the experiment that Faraday conducted. If a coil is subjected to an alternating current flowing through it, a fluctuating magnetic field is produced. This coil is called the transmitting coil. The magnetic field can induce current in another, receiving coil if located at a sufficient distance from the transmitting coil. The receiving coil is not connected to any power source. See Figure 2.2 for an illustrative explanation of the induction phenomenon.

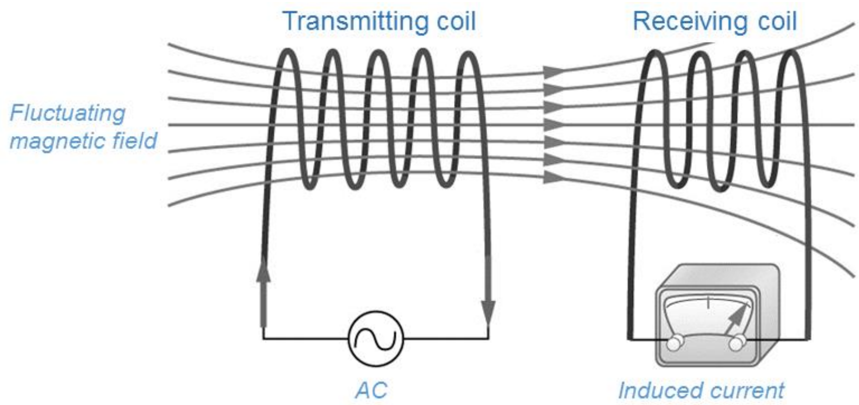


Figure 2.2: Illustrative explanation of the induction phenomenon. Picture retrieved and modified from Urone et al. (2018, Figure 23.9.1).

In the figure, the fluctuating magnetic field is represented as the grey arrows. AC is the alternating current which is the power source. The instrument shown is a galvanometer which shows that current is induced in the receiving coil.

This example shows the basics in how induction is created, and is similar to the one Faraday once upon a time did when he discovered the phenomenon. Induction has since its discovery, been useful in many applications. In the following section, the wireless charging of an electric vehicle using induction is explained.

2.3 Inductive Charging in Electric Vehicle

Inductive charging, or wireless charging, is when the induction technology is used to charge devices. When it comes to inductive charging of an electric vehicle, basically, one component will be placed separated from the car and one attached to the car. The component that will be separated from the car could for instance be placed on the ground, or where it best will connect to the other component wirelessly. However, the development of the inductive charging system indicates a trend of placing it somewhere below the vehicle. This component is the transmitting component which is also known as the ground assembly (GA). The component attached to the vehicle is the receiving device which is known as the vehicle assembly (VA). The GA is connected to a power source which provides alternating current (AC). This is in some cases called the wall box, which is a power supply box installed on the wall in, for instance, the garage. The GA consists of a coil, and when current is flowing through the coil, a magnetic field is generated. Due to an alternating current, the magnetic field will fluctuate, meaning it changes. When the VA is placed at a sufficient near distance from the GA, the magnetic field will induce current in the receiving coil. This current will then charge the battery which is powering the vehicle. However, the battery is driven on direct current (DC). Therefore, an inverter that transform AC to DC is needed. In Figure 2.3, an illustration of how the inductive charging in a vehicle works is shown.

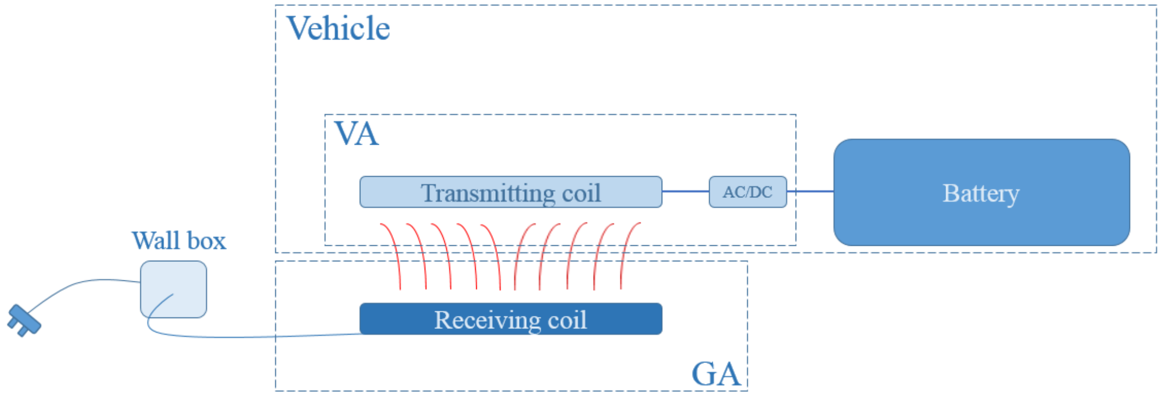


Figure 2.3: Conceptual illustration of inductive charging in a vehicle.

The red lines represent the magnetic field and thus the wireless connection between the coils. In VA, the current inverter (AC/DC) is included. In this case, it is included because it could be of interest in the development of the inductive charging in the VA. The vehicle is only illustrated as a dashed box. This is because no assumption of the positioning should be taken from the figure. Also, the figure does not reveal that the GA system has to be located under the VA system. It is only to make a graphic illustration making it easier to understand the technology.

Regarding positioning, the vehicle coordinate system is describes in next section. This coordinate system will be referred to when describing position in the report. The section follows by a description of the ground clearance of the car which had an impact of the result.

2.4 Vehicle Coordinate System and Ground Clearance

A coordinate system enables a standardised way of describing location and orientation within a volume (Schaub & Junkins, 2003). The coordinate system in a vehicle is described in Figure 2.4. The x axis is pointing in the longitudinal direction while the y axis in the transverse direction of the vehicle. The z axis describes the vertical direction, in other words, the height of the car.

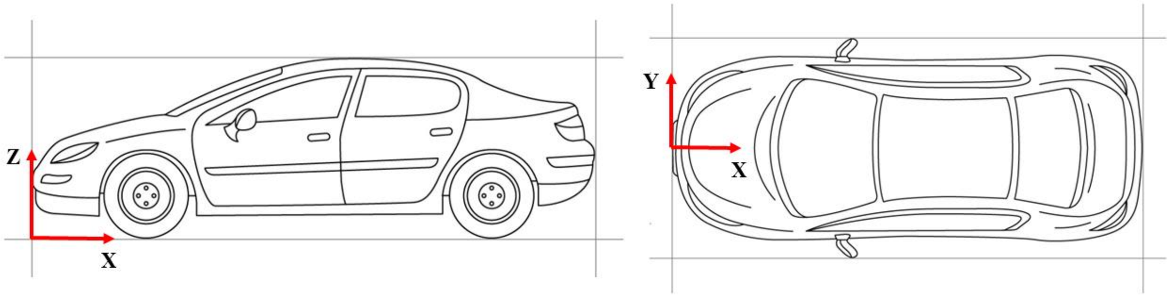


Figure 2.4: Coordinate system of a vehicle.

The distance between the lower end of the vehicle and the road is called the ground clearance, see Figure 2.5. The ground clearance is always the lowermost part, and is one of the most critical dimensions of a car. A high ground clearance means a large distance between the car and the road. This is beneficial when driving on bumpy and rough roads. The ground clearance is one of the parameters which defines the class of the vehicle, such as a sport car or SUV.

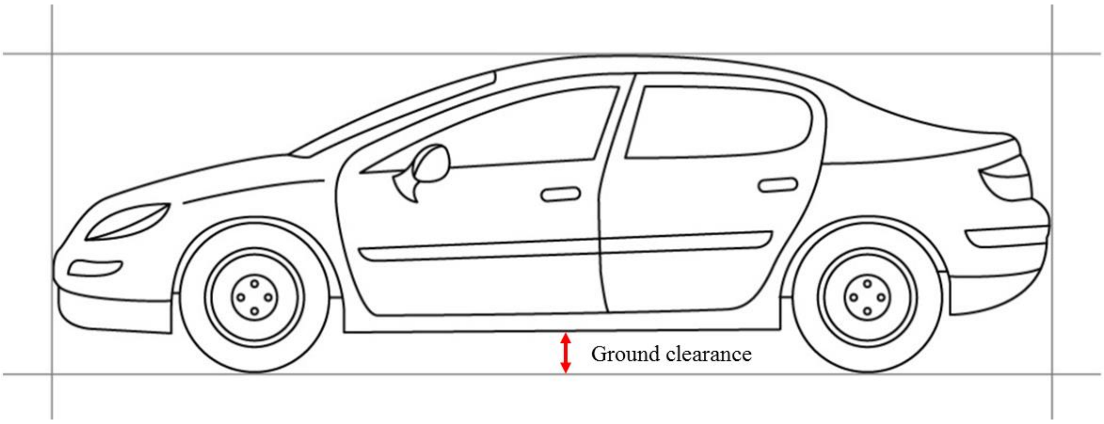


Figure 2.5: Simplified visualisation of the ground clearance of a vehicle.

When designing a vehicle, there are different ground clearances which need to be considered. For instance, there are curb stone ground clearances. If the vehicle drives on a curb stone, these constraints avoid the curb stone from damaging sensitive parts in the bottom of the vehicle. There are also dynamic ground clearances due to the motion and dampening of the vehicle. Other phenomenon are likely to occur in the middle part of the vehicle which put other limitations of the clearance.

2.5 Wireless Power Transfer Guideline

A standard has been used as a guideline when designing the VA. SAE International has published the recommended practice, SAE J2954, for Wireless Power Transfer (WPT), for light-duty plug-in/electric vehicles and alignment methodology (SAE International, 2017). The practice defines criteria for interoperability, electromagnetic compatibility, electromagnetic field, minimum performance as well as safety and testing. The SAE guideline published in 2017 only covers stationary charging, with the plan to include dynamic charging in the updated 2018 publication. Stationary charging means that the electric vehicle will only be charged when the motor is turned off, while dynamic charging enables charging of the battery while driving. The recommended practice is industry-wide, based on testing with the purpose of making the charging process more convenient and standardised. The guidelines can be used for development of the WPT technology to ensure compatibility with other systems.

SAE International recommended practice includes specifications of WPT power classes together with VA coil ground clearance range. The VA coil ground clearance is by the practice defined as “the vertical distance between the ground surface and the lower surface of the VA Coil” (SAE International, 2017, p.8). The distance is described in Figure 2.6.

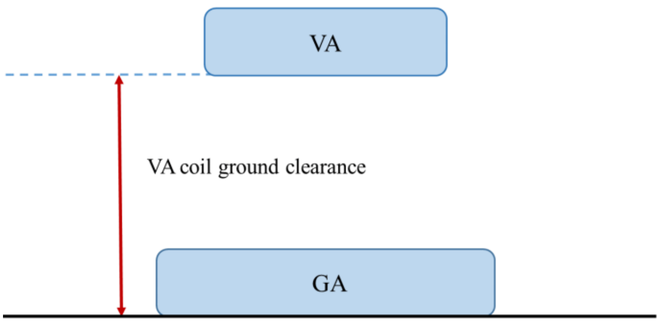


Figure 2.6: Illustration of VA coil ground clearance.

There are different coil ground clearance classes. The classes depend on, for instance, what car type the VA is attached to. According to SAE International, there are three coil ground clearance classes: Z1, Z2 and Z3, see Table 2.1.

Table 2.1: VA coil ground clearance range for the different Z-classes.

Z class	VA coil ground clearance range
Z1	100 - 150 mm
Z2	140 - 210 mm
Z3	170 - 250 mm

Four different WPT power classes are covered within the standard. The classes are divided depending to their maximum power input. The classes together with their input can be found in Table 2.2.

Table 2.2: Maximum power input for the four WPT classes.

	WPT1	WPT2	WPT3	WPT4
Max. power input	3.7 kW	7.7 kW	11.1 kW	22 kW

The WPT power level together with VA coil ground clearance are critical parameters for the system's performance. The parameters need to be considered when dimensioning the receiving coil in the VA. SAE International recommended practice defines the mechanical specifications for the coils, together with ferrites and housing for required power level and VA coil ground clearance. This will be specified later in the report when these specifications are utilised.

Due to the wireless charging of the vehicle, the VA will expose magnetic field. This exposure of magnetic field has to be controlled so that the VA does not disturb surrounding appliances. SAE International covers different standards about electromagnetic compatibility (EMC). EMC is about a component's ability to work within a system without disturbing other electronic components or appliances within the system.

3 Methodology

In this chapter, the methodology used throughout the project is explained. Also, the methods utilised are presented and described. In the project, knowledge gained from courses taken both in the bachelor programme Mechanical Engineering and the master programme Product Development at Chalmers University of Technology have been utilised. Most of the methodology is inspired by the generic product development process described in Product Design and Development (Ulrich & Eppinger, 2012). However, complementary material and methods were also utilised to cover all tasks and aspects of the work. The process and methods were modified to suit the project.

The work was structured and divided into six phases: Technology and Stakeholder Analysis, Problem Decomposition, Positioning Concept Development, Geometry Concept Development, Detailed Design, and Final Design, see Figure 3.1. The phases were executed in a chronological order and the results of each phase laid the foundation for the next. However, in some cases, iterations were needed. Therefore, going back to a previous phase was necessary to make progress in the project. The duration of each phase differed depending on its scope.

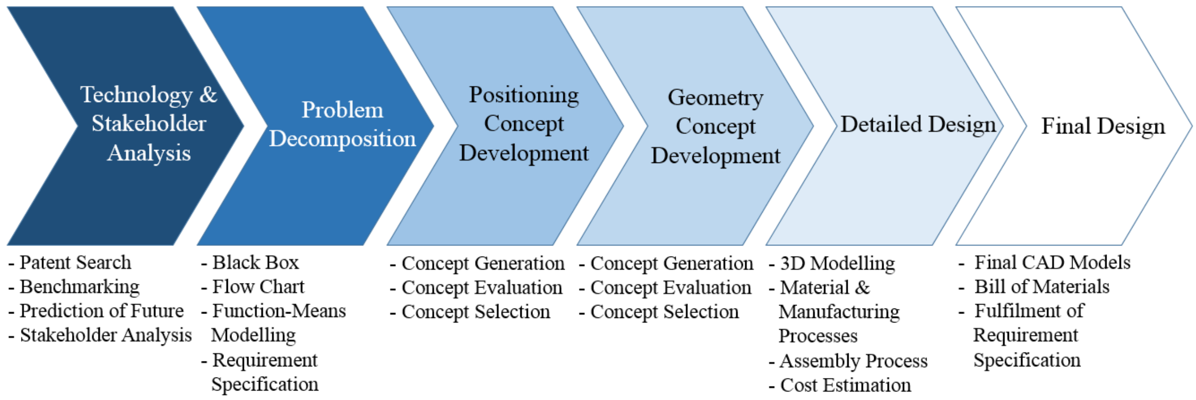


Figure 3.1: The six phases show how the work was structured.

In the figure, it is explained which tasks and methods that were undertaken in each phase. In the following, the chapter is divided into each stage of the development process where the methods used for each phase are explained. More thorough explanations about the execution of each phase are presented in each corresponding chapter later in the report.

3.1 Technology and Stakeholder Analysis

First in the process, a prestudy was undertaken. This prestudy involved technology and stakeholder analysis. In the technology analysis, a patent and different benchmark searches were executed. Also, a prediction of future wireless charging systems was included in the analysis. The patent search approach was mainly inspired by Haldorson (2016). The patent analysis was performed to be aware of what kinds of patents that have been applied within the wireless charging system and to be inspired for the forthcoming development work. The patent database Espacenet was used when searching after patents. The patent search was followed by benchmarking. In a benchmarking, competitive products and solutions could be examined which could be of high importance when developing and designing new solutions (Ulrich & Eppinger, 2012). In this way, the likelihood of developing a successful product increases. The prediction of wireless charging analysis was based on articles on the subject but also what competitors have told about their launching in the near future. This analysis also covered an overview of the history of wireless charging. In this way, an attempt in predicting the future development of the inductive charging system could be made. In the stakeholder analysis, the stakeholders of the project were investigated. A stakeholder is a person, or group of people, that are affected by the development of the product or component (Ulrich & Eppinger, 2012). This analysis was crucial in order to be able to cover all stakeholders' demands and wishes of the component being developed. The technology and stakeholder analysis laid the foundation for the forthcoming development work.

3.2 Problem Decomposition

After the technology and stakeholder analysis, a decomposition of the problem was executed. This involved the identification of main and sub function of the system, together with component carriers. Also, a requirement specification was established. This phase of the process was necessary to be able to later initiate the actual concept development process with concept generation and selection. The work done in defining functions included several methods and models. The tools used in the functional description were black box model, flow chart and function-means modelling.

From the black box model, the main function of the system was defined. The next step was to identify the sub functions of the system. The model used for this identification was the flow chart. This chart decomposes the main function into sub functions to decrease the complexity of the problem (Ulrich & Eppinger, 2012). Compared to the black box, the flow chart virtually describes the sub systems and flow of operands within the system. This gives an understanding of the process within the black box. Based on the flow chart, a function-means model was established. This model explains in a systematic way which function carriers are needed to solve the functions on each hierarchical level (Almefelt, 2017). By defining the functions on each level, sub systems or components accomplishing each function could be identified.

After all functions, components and sub systems were defined, it was more evident what specifications the component being developed had to fulfil. Based on this and together with the information from the technology and stakeholder analysis, the requirement specification was established. The requirement specification is a list of all the demands and wishes stated by the stakeholders. The list specifies which criteria the product, or concept, has to fulfil (Ulrich & Eppinger, 2012). The criteria could be a demand which has to be fulfilled, or a wish which are less critical, but could be of advantage to fulfil in order to be competitive. Except these criteria, the requirement specification declares the target value, verification method and stakeholder for each criterion. A target value specifies what the criterion needs to fulfil, the verification method how it is checked if the criterion is fulfilled, and the stakeholder from who the criterion is formulated.

In this project, the actual concept development process was a critical and large part of the work. Therefore, the concept development process was divided into two phases: positioning and geometry. These are explained in the following sections.

3.3 Positioning Concept Development

Normally, the concept development process includes several iterations of concept generations and screenings. Initially, a large number of ideas which solve the problem is generated. This number of concepts is later narrowed down when evaluating and comparing concepts. Then, another iteration of generation and elimination could occur, meaning the number of concepts again could increase and later decrease. Figure 3.2 visualises how the number of concepts can increase and decrease in the concept development process using several iterations. This approach was used in the concept development of generating and screening positioning concepts.

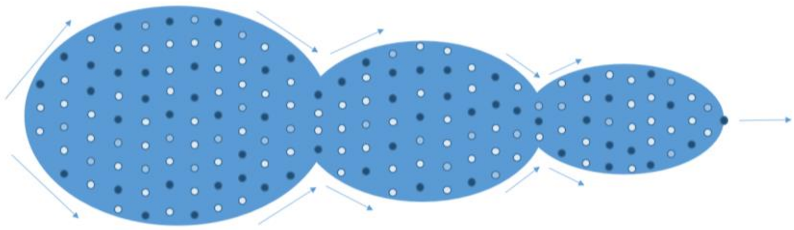


Figure 3.2: Illustration of how the number of concepts could increase and decrease during concept development.

This first phase of the concept development process started with investigating a general vehicle. Since a car is a large and complex system, it was decided to define the design space of the vehicle where the component under development could be positioned. This decision was based on the initial investigations of a car. When the design space was set, the platform of interest was examined and the generation of positioning concepts initiated. The method used for this generation was brainstorming. Brainstorming is a creative method where the participants are encouraged to generate a lot of ideas even though the ideas may not seem realistic (Ulrich & Eppinger, 2012). By allowing people being creative and thinking outside the box, ideas which no one had thought of before could occur. Several brainstorming sessions were undertaken. Both individual and group sessions within the project group were performed. Brainstorming can also be executed by utilising individual's knowledge outside the project. By using different individuals and groups, the chance of generating more and possibly better concepts is greater. The generation process, however, did not only use the creative mind of the participants. The generation was also based on the results achieved from the technology analysis. In this way, competitors' solutions could be utilised as inspiration for the concept generation.

The generation resulted in a vast number of positioning concepts. In several iterations, the number of concepts were narrowed down. In these screenings, different methods were used. To be able to narrow down the large number of concepts in the beginning, an elimination matrix was used. In this matrix, the concepts are evaluated based on demands from the requirement specification. Concepts that clearly do not meet the requirements are rejected (Almefelt, 2017).When unrealistic concepts had been eliminated, the next step in the process was to evaluate the remaining concepts. From the evaluation, it was realised that the concepts could be divided into different sections based on their placement in the platform. The positioning concepts located at a similar position were clustered into one section. These sections were then in focus for the remaining development of positioning. In the next screening iteration, the concept screening matrix was utilised. With this tool, the concepts are compared against each other using several criteria. These criteria could for instance be demands and wishes from the requirement specification. Normally, the concepts are compared to a reference concept. This reference could for instance be a current solution or one of the concepts developed. By investigating how well each concept performs or fulfils the criteria in comparison to the reference, the concepts get score values and are ranked. This results in that more concepts could be screened out from the development process. (Ulrich & Eppinger, 2012) In this case, the sections were subjected for the comparison in the concept screening matrix. However, the concepts were not forgotten. In the next phase of the concept development, features of some concepts were used when generating concepts for the geometry of the component. Several iterations of the concept screening matrix were necessary to be able to eliminating sections. When only few proposals of placement remained, discussion within the project group as well as with expert at Volvo Cars took place. Based on this evaluation, a final position of the component being developed was determined. This positioning concept determined the placement where the wireless power transfer occurs, in the coil.

3.4 Geometry Concept Development

The next phase of the concept development process was the geometry determination. This phase was more of a system-level design phase which, according to Ulrich & Eppinger (2012), for instance includes the product architecture and preliminary design of components and sub systems. Here, complete concepts of the geometry were generated which included placement of the electronics needed in the VA. When referring to the term electronics, all electronic components were included. However, the coil and ferrites were not comprised in this term.

Before the idea generation of the complete VA concepts was executed, some constraints of the component had to be determined. This included the determination of different components' design and features that had to fit in the component being developed. This also resulted in that a volume of the electronics could be determined. However, the shape of the electronics was not fixed. This allowed for different proposals of geometry when generating concepts. Except volume determination of the electronics, the coil topology was determined. Different coil topologies were compared and later evaluated to choose the most promising idea. Also, an investigation of components that already existed in the platform was performed. This was done to understand if there were any possibilities in integrating and utilising other components' features in the performance of the component being developed.

When these restrictions were defined, the actual development of the geometry was initiated. This involved the generation of complete concepts, evaluation and comparison to be able to eliminate concepts, and the selection of a final concept. Complete concepts were generated by first generate concepts of different sub functions/components of the system. These concepts were then combined in morphological matrices. A morphological matrix is a tool used to generate total solutions by combining different sub solutions that accomplish the sub functions of the total system (Almefelt, 2017). Methods used for generating ideas were the creative methods brainstorming and braindrawing. Braindrawing is similar to brainstorming, but only sketches are used to present ideas (Wiberg Nilsson, Ericsson & Törlind, 2015). Each participant sketched ideas of the geometry on a paper. After five minutes, the participants switched places and continued working with the paper in front of them. It was then possible to get inspiration from the other but also build upon the other participant's ideas. After the braindrawing session, all ideas were summarised and concretised. Also, in this early phase of the concept development, computer aided design (CAD) modelling was utilised. The CAD software used throughout the project was Catia V5, which is the software used at Volvo Cars. In a convenient way, the ideas generated from the sessions could be modelled and immediately be inserted to the platform of interest. In this way, it was easy to make modifications to better fit in the platform.

When several concepts had been generated, these were evaluated and compared against each other using concept screening matrices with criteria taken from the established requirement specification. Through iterations, the number of concepts could be narrowed down. The final concept to focus on in the forthcoming detailed design were chosen through discussions with employees at Volvo together with analysis within the project group.

3.5 Detailed Design

When the final concept was chosen, the next phase in the project was to realise the concept more in detail. In this phase, all parts of the vehicle assembly were modelled in Catia V5. Some of the components that were affected of the development of the VA was modified. Also, it was more thoroughly explained how the integration with the different vehicle components could be realised. The modelling often resulted in several design suggestions. In the cases where a certain design of a component had to be determined, the choice was supported by discussions and/or decision matrices. The decision matrix used for this purpose was the concept screening matrix.

The material as well as manufacturing process selection were performed in the detailed design phase. Initially, a screening of existing components was performed with the purpose to understand common used material classes for the components. This, together with a study of specific properties resulted in a selection of material class for each part. The software CES EduPack was utilised to be able to conduct more thorough investigation of materials. Promising materials were plotted in trade-offs diagrams to be able to find advantages and disadvantages of each material. Based on this, suitable materials were selected for each component of the VA. The manufacturing process for each part was based on, amongst other properties, the material chosen. The manufacturing process selections were supported by the compatibility matrices according to Ashby (2011).

Also, design for assembly and cost estimations were performed in the detailed design. Design for assembly has to be taken into consideration since the assembly process should be as convenient as possible. First, the order of the process was decided. Then, each step was examined to get a perception if the design of the vehicle assembly could be optimised for the assembly process. The cost estimation was based on the manufacturing cost for the included components in the vehicle assembly. These costs were calculated in the CES EduPack software. The cost estimation was roughly calculated and based on several assumptions.

Throughout the detailed design phase, environmental aspects, design for manufacturing and assembly, as well as cost and weight were taken into consideration. Also, ethical aspects were taken into consideration since no one should be affected negatively by using the wireless charging. In this case, the focus was on the attempts to avoid the exposure of magnetic fields. In situations where it was impossible to fulfil all aspects equally, trade-offs between these aspects were made.

3.6 Final Design

In this phase, the final concept of the VA was more thoroughly presented. Also, the vehicle components that were in need of modifications to be able to fit the VA in the platform are presented. To get a clear overview of the concept, an exploded view of the VA together with a bill of material were conducted. The bill of material states the quantity, material and mass of each component developed in the concept. The final design chapter ends with a fulfilment of requirement specification. Here, it is evaluated if the demands and wishes of the VA have been achieved or what is needed for the further development to fulfilling these.

4 Technology and Stakeholder Analysis

In this chapter, investigations regarding the technology for the future installed vehicle assembly induction plate have been performed. Both patent and different benchmark searches have been executed and are described. Since no standard regarding placement of induction plate yet was established on the market, the goal with the analysis was to find a trend regarding placement and possibly identify a pattern regarding other properties. The chapter also includes an attempt to predict the future for the wireless charging system. This to understand the needs and expectations of this technology in the future electric vehicles. In the final section of this chapter, a mapping of stakeholders is performed. This to comprehend which stakeholders that had more influence and impact in the project than others.

4.1 Patent Search

In this following sections, the strategy for the patent search as well as the result from it are described. Two kinds of search approaches were utilised, landscape and screening searches. The patent analysis served mainly as an inspiration source for the forthcoming concept generation phases and to discover possible market trends. The objective of the patent search was therefore not to ensure that the development of the VA would not infringe any patent claimed.

4.1.1 Patent Search Strategy

The patent search approach used was similar to the one according to Haldorson (2016). The patent search began with answering the questions: *what problem does the invention solve? what is the invention?* and *what does the invention do?* By answering these questions and later use keywords from the answers as well as synonyms of the keywords, appropriate search strings could be generated.

The patent search was conducted at the patent database Espacenet. To start with, relevant patent classifications were found. This to be able to narrow down the later searches. Some of the keywords and synonyms generated were combined into a search string. The classification system used was the International Patent Classification. The relevant classifications were utilised together with keywords and synonyms for conducting searches and find interesting patents. When classes were found, landscape searches were performed where a large number of patents were shown. This was done to get an overview of how many patents that have been applied in the recent years. In this way, the trend for the technology could be obtained and indicated. After the landscape searches, more thorough screening searches were conducted. The objective for these searches was to get a perception of what kind of patents that has been applied and to later get inspiration for the solution.

4.1.2 Patent Search Formulation

It was found that the question *what problem does the invention solve?* had several answers, where two of them were decided to use in the patent analysis. One problem could be the need of a cord to be plugged in to the vehicle when charging the battery. The user could easily forget to plug in the cord which results in that the car will not be charged. Since Volvo Cars, together with suppliers, already tried to develop and integrate the technology into the vehicle, the other problem discovered was that their current solution does not fit in the vehicle. Therefore, the advanced patent search was conducted in two parts, using the both answers of the questions. The answers together with corresponding keywords and synonyms are found in Table 4.1 and Table 4.2.

Table 4.1: Keywords and synonyms generation of the plug in problem.

Question	Answer	Keywords	Synonyms
Utility: What problems does the invention solve?	Difficult to remember to plug in the cord to the vehicle to charge the battery	Vehicle, battery	Car, driver
Structure: What is the invention?	An inductive charging (wireless charging) solution so that the battery in the vehicle can be charged automatically when the car is parked nearby GA (transmitting device)	Induction, wireless, parking, coil, magnet, electric, current	Cordless, receiving
Function: What does the invention do?	Charging the battery automatically by induction technology without the need of having a physical connection between the charging devices (GA and VA)	Charging, automatic	

Table 4.2: Keywords and synonyms generation of the limited space problem.

Question	Answer	Keywords	Synonyms
Utility: What problems does the invention solve?	The receiving device (VA) of the wireless charging does not fit in the electric vehicle	receiving, wireless, charging, electric, vehicle	
Structure: What is the invention?	A compact inductive charging solution positioned to be able to connect to the transmitting component (GA)	Compact, inductive, position, coil,	Placement
Function: What does the invention do?	Fit in the vehicle and charge the battery when connected wirelessly to the transmitting device	Battery	

Patent classifications relevant for this patent analysis basically concerned transporting and electricity. See Table 4.3 for how the classifications are structured together with explanations of the classifications.

Table 4.3: Patent classifications used in the patent searches.

Classification	Explanation
B	Transporting
B60	Vehicles in general
B60L	Electric equipment or propulsion of electrically-propelled vehicles
H	Electricity
H02	Conversion or distribution of electric power
H02J	Circuit arrangements or systems for supplying or distributing electric power; systems for storing electric energy
H02J50/00	Circuit arrangements or systems for wireless supply or distribution of electric power

4.1.3 Landscape Searches

Two landscape searches were conducted; one by searching for patents about inductive charging in general; one about inductive searching in vehicles. The search strings and classifications used together with resulting hits are found in Appendix A1. The results of the landscape searches are visualised as charts in Figure 4.1 and Figure 4.2. The solid blue lines represents the number of patents applied for each year while the dotted lines are trend lines.

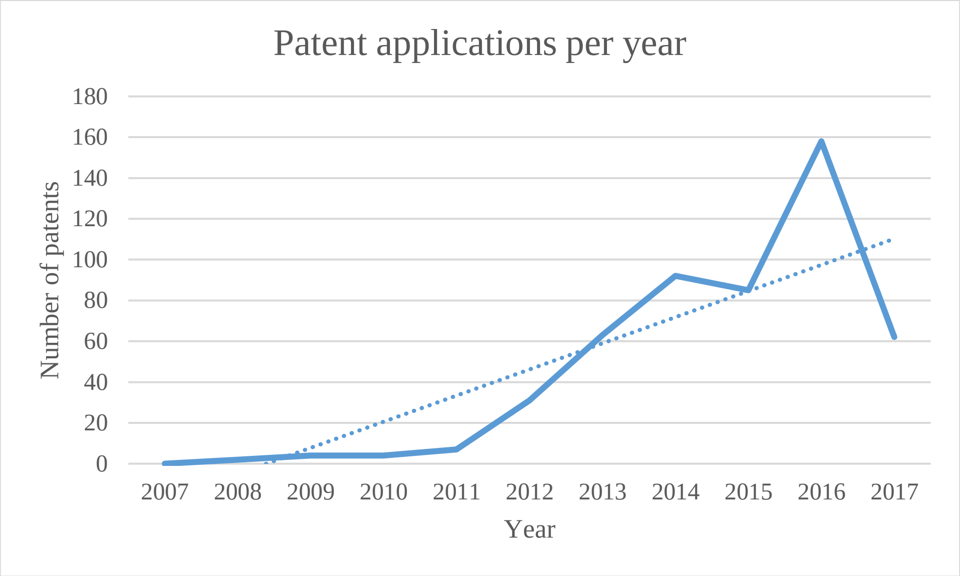


Figure 4.1: Graph of patent applications per year for inductive charging in general.

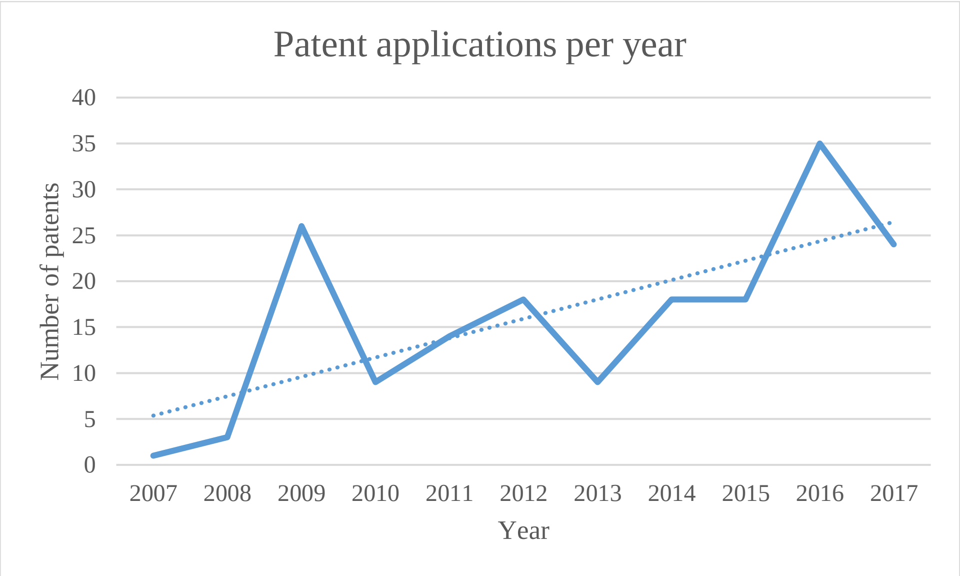


Figure 4.2: Graph of patent applications per year for inductive charging in vehicles.

In Figure 4.1, there is almost only an increase of patents applied. However, the number of patents seems to decrease in 2017. This decrease can most likely be described by that patents with recent filing date have not yet been published on the patent database. In Figure 4.2, the curve varies more up and down from year to year. The large number of patents in the year 2009 could be explained by that one company applied for many patents at that time. The dip in 2017 could be explained in the same way as for the chart above. Due to the dip of patents in 2017, trend lines were added to the charts. Both trend lines show that a steady increase of patents regarding inductive charging technology has been applied during these years.

Overall, the landscape searches showed that the patents about the inductive charging technology have been applied relatively recently. Mainly, it showed that there are a lot of patents and that the number mainly increases year by year. The landscape searches indicated that the inductive charging technology is an up going trend mostly.

4.1.4 Screening Searches

From the more advanced patent searches, six patents were found to be of interest to some extent. The results of these searches, together with utilised classifications, can be found in Appendix A2. Many of the patents were from China and also written in a Chinese language. There was difficulties in understanding the invention more thoroughly. Therefore, most of the understanding was achieved by looking at the drawings. An advantage with many patents applied in a certain area is that similar patents can be applied in another geographic area without being a risk of infringing a patent.

One patent, applied in China, was *Wireless charging device and charging method for vehicle*, CN106994908 (A). In this invention, the receiving device is installed on the lower part of a vehicle. This invention shows a sketch of the induction component, see Figure 4.3. It can be seen that the coil has a circular appearance.

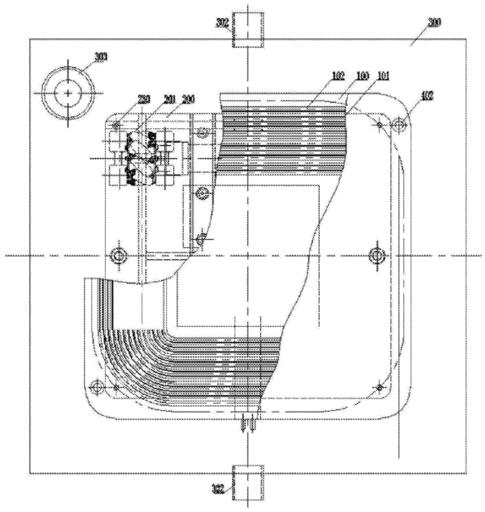


Figure 4.3: Patent CN106994908 (A). Picture retrieved from Espacenet (2018b).

In the patent, the position of the receiving device is determined to be installed on the lower portion of the vehicle. This gives a perception of a proper placement of component which could be of interest later in the concept development process. Other patents found to be useful when it comes to placement were CN105186611 (A) and JP2015208222 (A). They give a hint were the component successfully have been attached to the vehicle, see Figure 4.4 and Figure 4.5.

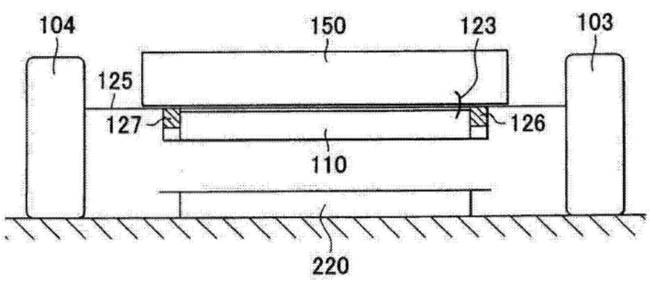


Figure 4.4: Patent CN105186611 (A). Picture retrieved from Espacenet (2018a).

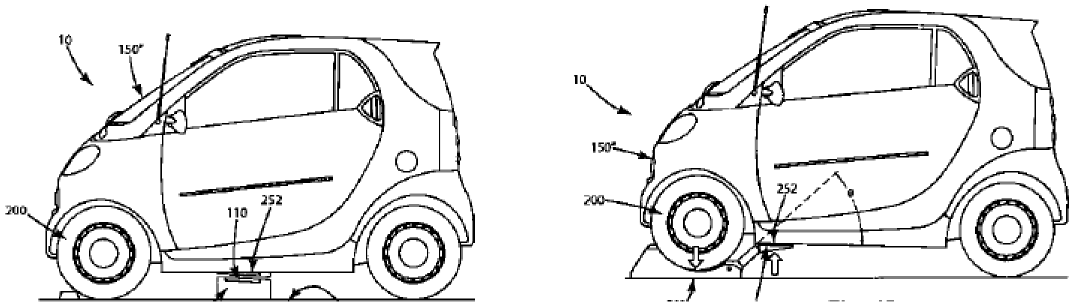


Figure 4.5: Patent JP2015208222 (A). Picture retrieved from Espacenet (2018c).

In Figure 4.4, it can be seen that the induction plate is attached below the vehicle, seen as 110 in the picture. The same is for the invention in Figure 4.5. The component is positioned below the vehicle and it can also be seen that it is located somewhere in the front/mid of the vehicle. A summary of all six patents are presented in Appendix A3.

The patent searches have given a perception of the trend and what kind of patents that are applied in the field of inductive charging. How the VA induction plate is positioned has been most useful in the patent investigation. However, this does not imply that the solution being developed must be positioned somewhere under the vehicle. It only gives indications of what others have done and what directions the market possibly pointing in, which could result in potential future standards. From the patent searches, it has also been noticed that many patents involve entire systems of wireless charging, such as the VA, GA and wall box together with additional features such as displays and cameras.

4.2 Benchmarking

After the patent search, further investigation regarding the technology was executed. Two benchmark searches were performed: competitor benchmarking and wireless charging technology within the automotive industry. The benchmarking was divided to cover a large area of interest. In the following, the method for carry out these benchmark searches is described followed by the results for each benchmark search.

4.2.1 Benchmarking Strategy

The competitor benchmarking was made to get an understanding of the current market. Since no standard regarding placement as well as functions of the VA were found, the analysis could presumably be an indication of the direction of a potential standard. The benchmarking focused on the entire induction system in the car. All information gathered was collected in tables to simplify the overview and comparison of the systems and technology.

To identify competitors which are developing and using the technology, the car market was scanned. This by going through competitor of Volvo Cars and investigate their technology concerning wireless charging. Also, companies offering solutions for aftermarket sales were identified. The information found was collected in a table to conveniently compare each brand, and possibly find a trend on the current market.

The benchmarking of the technology within the automotive industry was made similarly. Based on the information gathered, different technologies were identified. Deeper understanding of the system was collected by studying the companies. This information was gathered in a table for a clear overview.

4.2.2 *Competitor Benchmarking*

Inductive charging is a new technology on the car market, and there are only a few companies which have launched their systems yet. Therefore, it was difficult to find information about what is soon to be launched. However, almost all automotive companies are working with the technology but it is only a few that have released information. Only the companies which have revealed some information about their inductive charging system are listed in Table 4.4.

Table 4.4: Summary of competitor benchmarking.

Metric	Unit	Audi e-tron quattro	BMW 530e iPerformance	Mercedes-Benz S500	Ford	Porsche Mission E
Power input	**kW**	3.6	3.2	3.6		
Input Voltage	**VAC**		220			
Gap	**mm**	10		150		
Efficiency	**%**	ca 90	> 90	ca 90		
Charging time	**h**	0.5 = 80%	3.5			0.25 = 80%
Weight	**kg**	40				
Placement X		Front	Front	Front	Front	Front
Placement Z		Under	Under	Under	Under	Under
Positioning system		Parking assist	iDrive		Parking guidance	
Z movement	**Yes/No**	Yes, GA	No	No		
Protection		Small air gap		Detection system		
Market launch	**Year**	2018	2018	2018		2020

As seen in Table 4.4, information of data for some car brands is scarce. For instance, there is not much information about the inductive charging technology of Ford. However, Ford has revealed that they will release electric cars that will be charged wirelessly by induction in the near future (McGoogan, 2017). The others have announced in what year the inductive charging will be available which varies between 2018 and 2020. All car brands examined will install the VA induction plate somewhere in the front of the vehicle, under the car. In the table, placement X is the placement in longitudinal direction of the vehicle, while placement Z is the placement in height. Z movement is if the GA/VA will lift up/down near the other device in order to reduce the gap between the inductive charging components when charging. Audi is the only brand who will have this feature. In their system, the GA will be moved towards the VA when the vehicle is charging.

No information was found that brands such as Tesla, Nissan and Chevrolet have or will have the inductive charging technology in their vehicles. However, Evatran with their technology called Plugless is offering inductive charging for Tesla Model S, BMW i3, Nissan Leaf and Chevrolet Volt. The information about each system is collected in Table 4.5. Evatran offers the product for aftermarket sales and has independently developed the technology. The technology is placed under the car, and the distance between GA and VA is 100 mm in all cars. However, the positioning of the technology, power input and charging time differs. BMW, Tesla and Chevrolet have the VA placed in the front compared to Nissan where it is installed in the rear of the vehicle. The power input of BMW and Tesla are higher which probably also explains the shorter charging time. (Evatran Group, 2018)

Table 4.5: Summary of Evatran Plugless technology.

Metric	Units	Evatran Plugless BMW i3	Evatran Plugless Tesla Model S	Evatran Plugless Nissan LEAF	Evatran Plugless Chevrolet Gen 1
Power input	**kW**	7.2	7.2	3.3	3.3
Input Voltage	**VAC**	208-240	208-240	208-240	208-240
Ground clearance	**mm**	178	178	178	178
Gap	**mm**	100	100	100	100
Efficiency	**%**	84-90	84-90	80-90	
Charging time	**h**	1.67	1.67	6	3-4
Operating temperature range	**°C**	-30 to 50	-30 to 50	-30 to 50	-30 to 50
Dimensions VA	**mm**	406x838x25	406x838x25	464x762x127(32)	464x762x127(32)
Dimensions GA	**mm**	470x559x68.5	470x559x68.5	63.5x559x470	63.5x559x470
Weight	**kg**	12	12	12	12
Placement X		Front	Front	Back	Front
Placement Z		Under	Under	Under	Under
Positioning system		Parking assist	Parking assist	Parking assist	Parking assist
Z movement	**Yes/ No**	No	No	No	No
Protection		Detection system	Detection system	Detection system	Detection system
Market launch	**Year**	On market	On market	On market	On market

The information gathered from Table 4.4 and Table 4.5 indicates a power efficiency between 80-90 % of the system. Today, the power input differs between 3.2-7.2 kW, and a distance of 100-150 mm between the GA and VA seems to be most common. Notably is that Audi has a movement in z direction of the GA to decrease the distance between the VA and GA when charging to 10 mm. Audi claims that the decrease of distance increases the efficiency, and also protects the charging from foreign objects (Audi, 2015). Other competitors are using a detection system which turns off the charging system if foreign or living objects is too close the induction plates.

All solutions included in the analysis needs a system in the car to handle the positioning of the VA over the GA. This to ensure an efficient charging of the vehicle. In the most cases, the charging system cannot be turned on if the parking is not correct. Audi, with their 'z mover', seems to be especially sensitive to the positioning.

Overall, the current market indicates a standard placement of the VA in the front under the car. The power input is currently under development and would probably soon reach 11 kW, which will be the power input for the developed VA induction plate. Today, some kind of positioning and parking systems are included in all solutions to ensure safe usage. All competitors seem to strive to decrease the charging time, weight and volume, but at the same time increase the efficiency.

4.2.3 Technology Benchmarking: Wireless charging in Automotive Industry

There are two main technology providers who hold most of the patents within the field of inductive charging. One is Qualcomm Halo using two technologies, Double-D (DD) coil topology and a Circular one (Qualcomm Halo, 2018b). The other one is WiTricity which only uses Circular coil topology. A visualisation of both technologies can be found in Figure 4.6. All their patents have not be found in the patent search, see Section 4.1, since they are not published yet. Most of the tier one suppliers of the technology have bought the companies' intellectual property, and can thereby use the technology. Tier one companies are direct suppliers to the company which is making the final product (Silver, 2016), which in this case will be Volvo Cars.

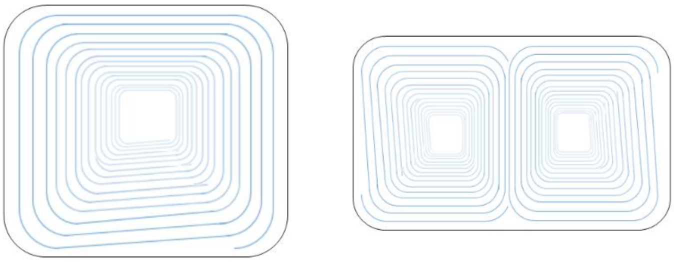


Figure 4.6: Circular coil topology to left and Double D coil topology to right.

Qualcomm Halo claims the importance of magnetic interoperability. Their technology has a standardised multi-coil as GA compared to the VA, which could be a single circular/square coil, multi-coil or a single coil solenoid. All different VA coils are supported by the same GA. (Qualcomm Halo, 2014)

WiTricity has over 240 patents granted worldwide, and over 195 patent applications pending (WiTricity Corporation, 2018). Their technology uses magnetic resonance, and is constantly under development. Many automakers and tier one suppliers including Toyota, Delphi, TDK, IHI and BRUSA are working together with the company. Also, General Motors and Nissan are working with the company to test the drive system (Hanley, 2017).

The companies claim that their system can fit a car in the range of sport to SUV. Notable is the power input and the system efficiency of their systems which are much higher than what is found about the competitors' systems, see Table 4.6. However, the power output of 22 kW will at present not be available for household installations (Halvorson, 2016).

Table 4.6: Summary of the wireless charging technologies.

Metric	Units	Qualcomm HALO	WiTricity
Coil topology		Double-D, circular	Circular
Power output	**kW**	3.7-22	2.6-11
Ground clearance		Low-High	Low-High
Efficiency	**%**	90+	91-93
Placement X		Front	Front
Placement Z		Under	Under
Positioning system	**Yes/No**	Yes	Yes
Z movement	**Yes/No**	No	No
Protection		Foreign object detection Living object detection	-

Later in the development process, a decision regarding coil design will be taken. It will be determined whether to use DD or Circular coil topology. The decision will mainly be based on which of these technologies best fits the geometry developed, but could also be based on other features, making the wireless charging most efficient.

Except to benchmark what is available at market and what other companies are doing within the subject, it could be of high relevance to examine what the future looks like for the inductive charging technology within the automotive industry. Since this system is about to enter the market in the coming years, one could predict the future for the technology. This prediction is done in the following section.

4.3 Prediction of Future Wireless Charging

To be able to predict the future of wireless charging in the automotive industry, a review of the history was necessary. The history will in this section be presented, followed by an attempt in predicting the future development of the inductive charging system.

4.3.1 History of Wireless Charging

Auckland University proposed in 1990 various induction power transfer systems for stationary electric vehicle charging (Covic & Boys, 2013). The systems included aluminium back plates, ferrites and coils. The inductive charging started with buses. In 2002, Wesedan University & Showa Aircraft Industry developed bus stops with stationary charging (Chun & Chris, 2017). It had an efficiency of 92-93 % at a distance of 100 mm for 30-150 kW. In 2011, Wave in USA followed and demonstrated a charging stop for buses with a 250 mm distance, 5 kW power transmission with over 90 % efficiency. Further, the company developed a 25 kW power transmission in 2013. At the same time, the company Bombardier Co. presented a bus stop with a power transmission of 200 kW. However, the first stationary charging system for passenger cars was demonstrated in 2011 by Qualcomm Halo, USA. It had a power input of 3.3-7 kW.

4.3.2 Future of Wireless Charging

The charging power seems to be of importance. Audi (2015) is working with a solution with a charging of 11 kW in the next generation cars. McDonald (2017) claims that the largest challenges in the future are to increase the power input and at the same time decrease the cost. Currently, the plug-in system offers a faster charging speed to a lower cost in comparison to the wireless system.

The wireless charging foresees to be a next step in the autonomous driving. Volkswagen having a concept called ‘Volkswagen V-Charge concept’ which consists of wireless charging pads installed in parking spots. The car could by itself find the nearest parking spot and begin to charging its battery. When finished, the car could leave space to let other cars charging their batteries. Schaal (2016) argues that some of the big problems with the EV charging eliminates with the charging spot solution.

Qualcomm sees even further into the future. The company are developing and testing wireless charging embedded in the roadways. The car could then be charged while driving (Qualcomm Halo, 2018a). Condliffe (2017) claims that the batteries then could be smaller, and thereby could the weight and cost be reduced. However, he also admits that it is not likely that all streets in the future will be embedded due to the infrastructure and cost of the systems.

About the cost, Schaal (2016) argues that the price of the equipment will follow the same pattern as other systems in the electric automotive industry. First, it will be expensive and thereby only for the high end market. However, the price will drop when the system works perfectly and it will enter the mass production. (Schaal, 2016). A more exact price tag for the wireless charging system has not been found.

4.4 Mapping of Stakeholders

In this section, the stakeholders of the VA induction plate being developed are identified. A mapping of stakeholders was made to ensure that all parties with an interest of the project was identified. The identification ensured that the needs of everyone that will be affected by the project were covered. In the following sections, the method for carry out the process of mapping the stakeholders is explained followed by the result from it.

4.4.1 Stakeholder Analysis Strategy

The stakeholder analysis was adapted from Mendelow (1981) and consisted of three steps: identification, prioritisation and understanding of the stakeholders. First, a brainstorming session was performed with the objective to cover internal as well as external stakeholders. The stakeholders' impact and influence within the project were then ranked in three levels: low, medium or high. The result was plotted in a matrix for an evident overview.

Further, important factors for each stakeholder were identified, together with an analysis of how they could contribute to the project. Complementary, scenarios of how they could block the project were recognised. Finally, strategies to ensure engagement of each stakeholder were accomplished. The result was summarised in a table.

4.4.2 Stakeholder Analysis Results

The mapping resulted in seven stakeholders with different interests in the project. The stakeholders were identified as being:

- Research and Development (R&D)
- Manufacturing
- Assembly line
- Service
- Sales
- End users
- Chalmers University of Technology

All identified stakeholders, excluding end users and Chalmers, are stakeholder within the organisation of Volvo Cars. The stakeholders and their needs, together with contribution possibilities and strategies to engage them are summarised in Table 4.7. The impact and influence of each stakeholder in the project can be visualised in Figure 4.7. The figure illustrates how to handle each stakeholder to ensure that their needs are covered in the project.

Table 4.7: Summary of all stakeholders.

Stakeholder	**Impact**	**Influence**	**Important for the stakeholder**	**How could the stakeholder contribute to the project?**	**How could the stakeholder block the project?**	**Strategy for engaging the stakeholder**
R&D	High	High	Concept which meets the requirements	Expertise knowledge	Not give enough information Change conditions	Continuous meetings/ discussions
Manufacturing	High	Medium	Possibilities to manufacture the concept	Communicate their needs	Making complaints too late	Design for X: Manufacturing
Assembly line	High	Medium	Possibilities to assemble Ergonomics	Communicate their needs	Making complaints too late	Design for X: Assembly
Service	High	Low	Possibilities for maintenance Ergonomics	Communicate their needs	Making complaints too late	Design for X: Assembly & life time
Sales	Medium	Low	Cost	Communicate their needs	Making complaints too late	Keep track of the cost
End users	High	Medium	Working product Usability Safety	Communicate their needs	Stop buying cars	User needs
Chalmers	Medium	Medium	Follow the guidelines for writing a master thesis	Supervision and reviews	Not give enough information	Continuous meetings

The R&D department at Volvo Cars had a huge impact and influence on the project. It can be seen in Figure 4.7 that the company is placed in the right upper corner. It is of high importance for the company that the concept meets the requirements. By contribute with expertise knowledge within the field, and not change conditions during the project, the department could ensure that the best result possible was reached. Continuous meetings and discussions with employees at the company was the key to engage the stakeholder during the project.

Both manufacturing and assembly line was affected by the project. They were thereby seen as stakeholders. This since the concept later on could be a component in their cars, which must have the possibility to be produced and installed. If the stakeholders complain about the design and position of the concept too late in the process, it could result in huge costs. Therefore, the stakeholders was involved in the project by taking the manufacturing and assembly aspects in mind during the entire project, especially in the detailed design phase.

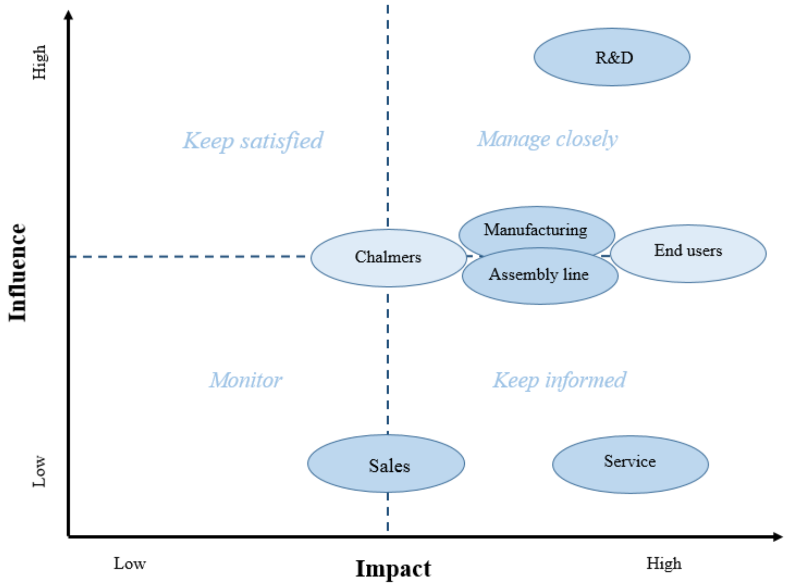


Figure 4.7: Illustration of how each stakeholder should be handled.

Also service and sales had an impact of the project later on in the process. In their case, the maintenance, ergonomics and cost were of importance. These aspects were also considered in the concept development and detailed design phases, and by keeping track of the cost in the entire development process.

Stakeholders outside the company were also identified. The end users, which are the car owners, are stakeholders of high importance. For them, a well performing and safe product which is easy to manage could be crucial. Otherwise, they will not purchase and utilise the product. Identification of their needs was therefore of high importance to avoid these stakeholders to block the project. Furthermore, Chalmers University of Technology was a stakeholder with interest in the project. Compared to the departments of Volvo Cars, it was important that the project followed the guidelines for writing a master thesis. To ensure that the guidelines were followed, continuous meetings with the Chalmers supervisor were structured and executed.

4.5 Summary Technology and Stakeholder Analysis

The chapter started with patent searches, both landscape and screenings, to find trends and to get inspiration for the development. The landscape search showed that the patents about inductive charging have been applied relatively recent, and the number of patents mostly increasing year by year. The screening search indicated on a trend of placing the VA under the car.

The benchmarking indicated a similar trend of putting the VA under the car and it also showed a trend of positioning it in the front. Two main technologies for the coil design were found, Circular and Double D. The technologies were patented by two companies, and most of the tier one suppliers of the technology have bought the companies' intellectual property and could thereby use the technology. The prediction of the future showed a trend of placing charging plates on parking spots, and also ideas of charging while driving.

Finally, the stakeholder mapping was executed. The mapping indicated importance of manage the R&D department, manufacturing, and assembly line at Volvo Cars closely. Also, the end users need to be taken into consideration during the entire project.

5 Problem Decomposition

The chapter involves the work done by clarifying which functions that are needed for the VA system to work. First, the flow of operands was identified. These were used to define the main function of the system. Then, sub functions within the system as well as components/sub systems needed to accomplish each function were identified. Finally, a requirement specification was established based on acquired knowledge from the market analysis and function decomposition, as well as demands from the different stakeholders.

5.1 Functional Description

In the following, the methodology applied for the functional description is explained together with its result. It concerns the identifications of both functions and components within the system. The functional description involves black box modelling, flow chart and a function-means model.

5.1.1 Functional Description Strategy

The first step in identifying the functions for the VA system was to make a black box model. The black box represented the system under investigation. Only the flows of input and output operands of the system were visualised, not the system function. The inputs and outputs could for instance be the flow of energy, materials or signals in and out from the system (Ulrich & Eppinger, 2012). The black box model was made to get an overview of what the system needs to handle and from this, be able to define the main function of the system.

Based on the black box model, a flow chart was created. The chart decomposes the main function into sub functions to decrease the complexity of the problem (Ulrich & Eppinger, 2012). The graph visually describes the flow of energy and information inside the system which gives an understanding of the process within the black box. First, the system boundary was selected together with the outer components needed to create the main function. The flow of energy within the boundary was analysed to identify the transformation functions needed to fulfil the main function. When the flow of energy was recognised, the information exchange through the system was studied.

Based on the flow chart, a function-means model was established. This model explains in a systematic way which components are needed to solve the functions on each hierarchical level (Almefelt, 2017). The model was made according to Almefelt's (2017) visualisation of a function-means model. By defining the functions on each level, sub systems or components accomplishing each function could be identified. Acquired knowledge from the previous stages of the development process as well as help from colleagues at Volvo Cars were used to compile the models.

5.1.2 Black Box Modelling

In Figure 5.1, a visualisation of the black box model established is shown. Only the flow of input and output operands to and from the VA system is revealed. The flow identified was in the form of energy (solid arrows) and information (dashed arrows).

Figure 5.1: Black box model of the VA.

As seen in Figure 5.1, the energy flow input is a fluctuating magnetic field. The VA receives the magnetic field from the wireless connection with the GA. The energy flow output will be power in form of DC, which will be transferred to the battery pack in the vehicle. The system will also experience a flow of information. Information input could, for instance, be that the wireless charging system detects the VA within the system area, resulting in that the vehicle starts to charge. Also, information that the vehicle is fully charged could be an example of an information output.

With the help of the black box, the main function of the VA could be identified. The main function of the VA system was defined as:

Transform magnetic field into DC from GA to vehicle battery

5.1.3 Flow Chart

When the main function had been formulated, it was decomposed into sub functions within the system boundary. The system boundary of the flow chart was the VA system. The flow chart with its transformation functions can be found in Figure 5.2. The solid arrows indicate the flow of energy, the dashed arrows the flow of information while the dotted lines indicate material. The texts in italic describe what kind of energy that is transferred between the sub functions. The blue boxes symbolise transformation functions compared to the orange ones which are existing components in the wireless charging system or in the vehicle. The dashed line in dark blue that encircles all functions represents the system boundary. As seen in the figure, a transformation system was found inside the VA system. The system is symbolised with a dashed line in light blue.

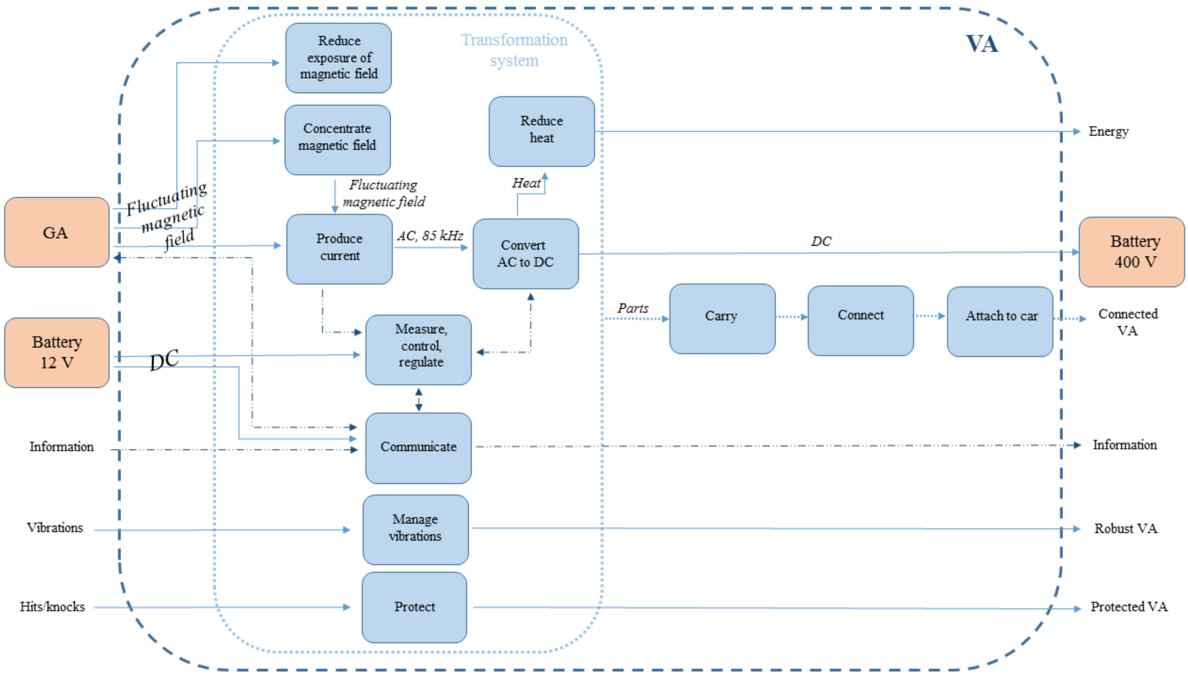


Figure 5.2: Flow chart with the VA as system boundary.

As seen in Figure 5.2, twelve transformation functions were found when analysing the VA. They were as follows:

- Reduce exposure of magnetic field
- Concentrate magnetic field
- Produce current
- Convert AC to DC
- Reduce heat
- Measure, control, regulate
- Communicate
- Manage vibrations
- Protect
- Carry
- Connect
- Attach to car

First, the GA generates a fluctuating magnetic field. As seen in Figure 5.2, the field needs to be managed in three different ways to fulfil the main function of the system. The field is concentrated to increase the coupling factor between the GA and VA which increases the efficiency. Reduced exposure of the magnetic field is needed to protect the surrounding from this kind of disturbances. Current is generated due to the fluctuating magnetic field in the GA. However, the current generated is alternating with a frequency of 85 kHz but the battery needs direct current to store the energy. Therefore, the transformation function *Convert AC to DC* is placed between *Produce current* and the *Battery 400 V*.

The transformation of AC to DC will generate heat which needs to be reduced. The transformation also needs to be measured, controlled and regulated to optimise the process. The necessary electronic equipment for the function needs electricity which are given by a 12

V battery. However, a 12 V battery already exists in the vehicle and function as a source for electricity for other components. Further, the VA is a part of a greater system and therefore needs to communicate with other components. Exchange of information is made by the transformation function *Communicate,* which is provided with electricity in the same way as the electronic equipment. The VA will be attached to the car which will result in vibrations which the component needs to handle. Together with these vibrations, the system could be exposed to hits/bumps from the environment. It is important that the system is protected to manage these hits/bumps.

Outside the transformation system, auxiliary functions are needed to handle the physical parts. The components which manage the transformation process need to be carried and connected to each other and to components within the car. Finally, the entire system needs to be attached to the vehicle.

5.1.4 Function-Means Modelling

When sub functions within the VA system were identified, these functions together with additional sub functions were utilised to understand which components or sub systems were needed to fulfil the functions. The model was made with the gained knowledge at this stage in the process, which means that other functions of the entire system could emerge later on in the development process. All these functions with related components were inserted in the function-means model, see Figure 5.3. The light blue boxes represent the functions on different hierarchal levels, while the darker blue boxes represent sub systems or components that fulfil each function connected to it. The main function of the VA is visualised in the top of the figure. Thirteen different sub functions were identified on the second level. Also, components to accomplish these functions were defined and are shown in the figure. Some of the components/sub systems that accomplish the functions are represented as question marks, (?). The reason for this was that these components could not be identified at this stage, or that high potential in possible further development was found. However, the components that have been able to be identified could also be up for development or optimisation.

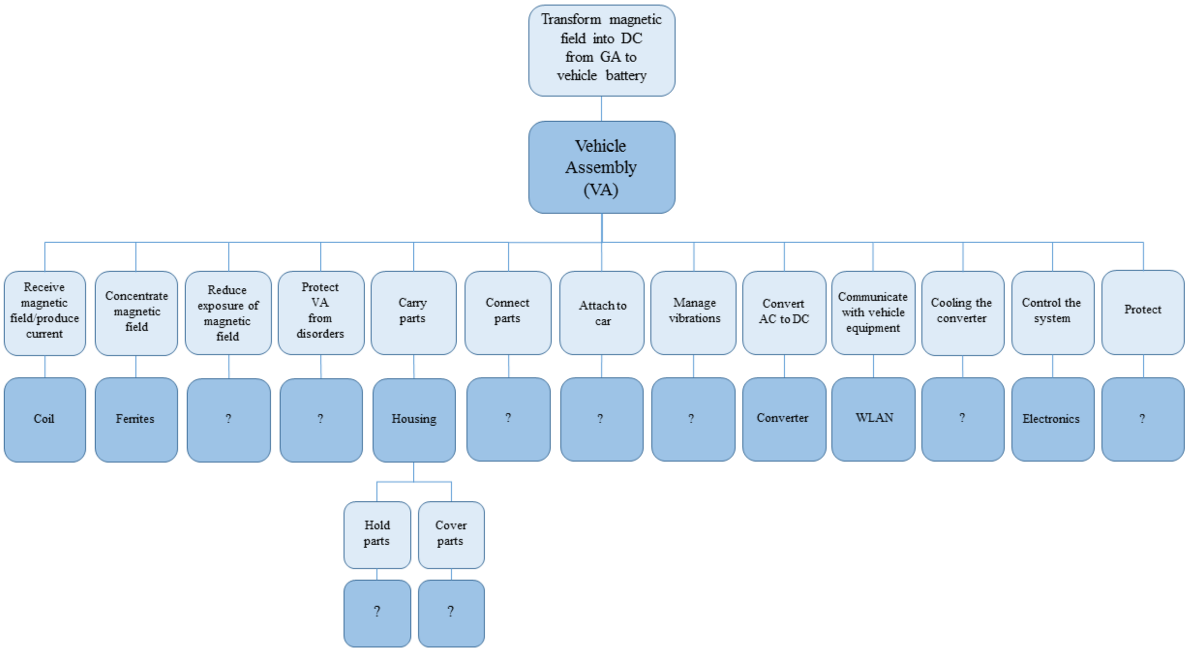


Figure 5.3: Function-means modelling of the VA.

The coil will be the component that receives the magnetic field and produce current from the wireless connection between the GA and VA. This kind of component in the VA is necessary to be able to generate current through the inductive charging technology. There are several coil designs available at the market which could be of interest to investigate. To make the power transfer between the GA and VA more efficiently, components concentrating the magnetic field are needed. This could be achieved by using ferrites. One function identified in the flow chart was to reduce exposure of magnetic field. This to avoid damage or disturbance of other equipment as well as the outer environment. A component to accomplishing this function has not yet been identified. The same applies to the function *Protect VA from disturbances*, see Figure 5.3. This sub function was identified from the function-means model which concerns the protection from, for instance, disturbance in forms of radio waves and other noises from different equipment.

A component will be needed to carry all the parts in the VA. This component has been identified as the housing. As seen in Figure 5.3, the housing has additional sub functions which are *Hold parts* and *Cover parts*. Components needed for solving these functions could be up for the continuing development. Another sub function in the VA system is *Connect parts*. The purpose of the sub system that will fulfil this function is to make a connection to all components and sub systems within the VA. However, the connected parts need to be attached to the car which will result in vibrations when the car is moving. How to solve these functions was up for development later on in the process.

As mentioned earlier in the project, the current generated in the VA is AC at a frequency of 85 kHz. However, the vehicle battery needs power in form of DC. Therefore, AC needs to be transformed into DC. This is done by using a rectifier which is a converter. The whole wireless charging system needs to communicate with the vehicle, meaning the VA has to be able to communicate with other equipment in the vehicle. For instance, the system has to know when, or if, the car needs to be charged, and when the charging should be switched off. To be able to communicate with other equipment, a Local Area Network connected to WiFi alternatively Bluetooth could be needed. In this case, a Wireless Local Area Network (WLAN) seems as the most appropriate. A WLAN is a way to communicate with other equipment wirelessly within a specified area (Mitchell, 2017).

The conversion of AC to DC will result in heat in the rectifier due to some power losses. Therefore, something to cool the rectifier will be needed, such as some sort of cooling system. This component has, however, been left with a question mark due to scarce knowledge, but could be up for development. However, VA system also needs to be controlled. This could be done using electronics, such as sensors and regulators. Finally, protection is needed to prevent the surrounding from damaging the system.

5.2 Requirement Specification

A requirement specification was compiled which included demands and wishes of the component under development. The specification was continuously updated throughout the project as new and more knowledge was acquired. However, the main part was set in an early stage of the project. In the following, the strategy of compiling the specification is presented together with its result.

5.2.1 Requirement Specification Strategy

A requirement specification was established based on the technology and stakeholders analyses performed, as well as demands and wishes from Volvo Cars and the project group. Also, standards and guidelines concerning the VA were covered. The specification was made to ensure that requirements and demands from different stakeholders were covered in the final concept. The requirement specification also helped to indicate which concepts to eliminate and further develop later on in the concept generation phases by examining how well each concept was fulfilling the wishes.

First, the technology analyses were reviewed. This to ensure that a competitive product will be under development. The review of the market was followed by collecting demands and wishes from the stakeholder analysis. The demands and wishes from the stakeholders ensured that different aspects of the product were covered during the development, for instance, manufacturing and service.

Internal demands from Volvo Cars were also studied. These were found by talking to employees at the company, together with a review of the company’s culture. Finally, demands and wishes from the project group were collected. However, all demands and wishes gathered during the studies were compiled into a requirement specification. The specification included criteria, target values, weighting of wishes, verification methods and stakeholders. The wishes were ranked in the scale of 1-5, depending on their importance, where 5 was most important. To be able to put a ranking on each wish, a weighting matrix was conducted. In this matrix, each wish was compared against each other, where 0 was less important, 0.5 equally important and 1 more important. Adding these values gave a total sum for each wish. After the result from the matrix had been evaluated, the rankings were determined. The demands were left without a rank since they were needed to be fulfilled. The verification method stated what method or test that will be undertaken to verify if the criteria is fulfilled. The main content of the requirement specification was set before the concept generation phases, however, the specification was revised during the project.

5.2.2 Final Requirement Specification

The requirement specification was divided into seven areas; performance, functional, installation and maintenance, manufacturing and assembly, geometry and placement, material, and non-functional. The areas eased the overview of all criteria, and were decided based on the collected demands and wishes. The final requirement specification can be found in Appendix B1. Below, the demands and wishes defined are explained. A verification method is stated for each criteria. One common verification method is 3D modelling which mainly covers criteria about geometry and placement. Another common verification was CES EduPack. Here, criteria regarding material constraints and manufacturing cost could be checked. The verification methods for all criteria can be found in the requirement specification.

The review of the technology analyses resulted in demands of power input and power efficiency. These were set as demands due to the competitor's technology and the prediction of the future. For instance, one demand was set to power input of 11 kW. The technology analysis indicated an increased pattern of these input, followed by the prediction of the future which confirmed the result. The product will, if realised, be a part of the future electric vehicles. The market will presumably be changed by then which makes the power input of 11 kW reasonable.

The standard SAE J2954, Wireless Power Transfer for Light-Duty Plug-In/Electric Vehicles and Alignment Methodology, by Society of Automotive Engineers (SAE) International, set the criteria concerning safety and magnetic fields. It was important that the concept should not be disturbed by, or disturb, electronic equipment within the car and its surrounding. The standard also stated demands concerning exposure of magnetic fields. This since the magnetic field generated could affect the health of a human being negatively. This standard resulted in criteria which were included in the functional area in the requirement specification. However, the standard also included performance criteria as well as demands concerning geometry and placement. Examples of these were the operating frequency of 85 kHz, ground clearance and coil and ferrites volume. All criteria taken from the standard were set as demands due to their high relevance of fulfilment.

Most demands and wishes were stated by the company, Volvo Cars. By examining the company's culture as well as contact with employees, it was found that all cars should have a life time of 15 years. This was also translated into cycles by assuming that the charging system will be used once a day, resulting in 5 475 cycles. Both these life time criteria were put as demands. In the category of performance, demands of strength and collision safety were also regarded. The strength criteria specified that the VA should manage its own load which was a demand. Two criteria concerning collision safety were defined. In a car crash, there should not be any risk of open electrical circuit. The other collision demand specified that the VA should not affect the deformation behaviour of the vehicle negatively.

Except the demands already mentioned based on the standard SAE J2954, the functional criteria defined were leakage proof, manage misalignments, impact resistant and compatible with critical vehicle components. Manage misalignments means that the wireless charging should work even though the car is parked with a smaller offset from the GA. This was set as a wish in the requirement specification. The other criteria was put as demands. In addition, the driving performance and customer experience should not be affected negatively. Instead, the concept should increase the overall experience of the car. Weight constraints were put as both a demand and a wish. The VA must not exceed 15 kg, but was desired that the maximum weight should not exceed 12 kg.

The VA should fit in Volvo's updated SPA platform, with the constraints of dimensions which follows. Therefore, the VA has to be compatible with the platform, meaning that few critical modifications of vehicle components should be made. Concerning the ground clearance, the VA should be compatible with the cluster 60, low vehicle. Since an aerodynamic design is of advantage, this was defined as a wish.

Since the component possibly could be implemented in future electric Volvo cars, manufacturing and assembly processes must match the company's processes. One demand put on manufacturing processes was that the VA should be possible to manufacture. However, a wish was stated that the manufacturing should be available in-house. The assembly process of the VA should be available in-house since the component will be included in the company's offerings. This also applies to the installation of the VA. Therefore, both these criteria were defined as demands. The number of components should be as few as possible since this could ease the assembly process. However, a low number of parts must not affect the manufacturing or other aspects. Low number of components was stated as a wish. No demand regarding maximum cost of the VA has been stated from the Volvo. However, the project group defined a maximum manufacturing cost of 1 000 SEK per VA as a target value.

When it comes to installation and maintenance, the VA should be reachable for service. Also, the placement of the VA should not prevent from reaching vehicle components nearby if maintenance is needed. Both these criteria were put as wishes. In the end of the life time, the component should be possible to disassemble to be able to separate the different materials. This criteria was put as a demand.

The last criterion area, material, covered environmental aspects as well as corrosion, water and chemical protections. The component should have a low impact on the environment and the VA should be resistant to different weather conditions.

In total, nine wishes were established. As mentioned, the wishes were weighted based on the relevance in fulfilling these. In order to make a fair ranking, all wishes were compared against each other in a weighting matrix, see Appendix B2. Depending on the sum for each wish, they were given a weight number between 1-5. Their given numbers are shown in the requirement specification in Appendix B1. In Chapter 9, when a concept had been determined and modelled, the fulfilment of the requirement specification was reviewed.

5.3 Summary of Problem Decomposition

A functional decomposition was made in order to gain a better understanding of the VA system. The black box resulted in the main function *transform magnetic field into DC from GA to vehicle battery*. Further, twelve transformation function were identified in the flow chart. These were used to build a function-means modelling which included sub functions together with its component needed to fulfil the function. Nine of the components/sub systems that accomplish the functions were represented as question marks. The reason for this was that these components could not be identified at this stage, or that high potential in possible further development was found. For instance, cooling the rectifier, attach to car and manage vibrations had potentials to further development.

In summary, a requirement specification was developed. The specification included all demands and wishes that appeared in the technology and stakeholder analysis, together with functions found in the functional decomposition. Complementary, the recommended practice SAE J2954 was put into the specification to ensure compatibility with other systems. The specification included seven categories: performance, functional, installation and maintenance, manufacturing and assembly, geometry and placement, material, and non-functional. The main content of the requirement specification was set before the concept generation phase, but some parts were updated during the project due to gained knowledge.

6 Positioning Concept Development

The concept development has been divided into two phases. The first development stage covered the placement of the vehicle assembly, which will be explained in this chapter. Here, the placement of the coil house was in focus. In the following, the methodology of the concept generation and selection of this phase is explained. This is then followed by the results of all steps and methods used.

6.1 Strategy for Generation and Selection of Positioning

The first iterations covered the placement of the VA. The objective was to find proper positions to place it in the vehicle. Since a car is a large system which consists of a lot of different components and sub systems, an initial screening of the design space was made. A traditional car was divided into nine zones, where the view perspectives from front, side and above were divided into three zones each. The focus in this first iteration of the placement generation was mainly to take customer experience into consideration, and not to look at the layout or the structure of the platform of interest. This was made by analysing consequences of placing the component in the different zones, together with its following result for the entire wireless system including the GA. All positive and negative aspects of placing the components in the different zones were summarised in pros and cons lists. The lists were then reviewed and evaluated in two cycles, one with the project group and one with employees at the company. This resulted in that some of the zones were eliminated for the continued development process.

The next step included analysis of the geometry in the zone selected for further investigation. A 3D model of the platform was used for the investigation. First, individual brainstorming sessions were undertaken which focused on finding available space without doing any modifications of the platform or vehicle components included. Based on that, sessions were held which focused on creating space by modify vehicle components. The sessions took place in several iterations.

Complementary to the individual brainstorming sessions, workshops with employees at the company were conducted. The goal was to get inspiration and ideas from people with more knowledge within the field and the platform. Totally, two sessions were held. The workshops started with an introduction of wireless charging and the component under development. A 3D model of the restricted area was given to the participants. They were told to find a space to place the VA system without doing any modifications of the platform. Following, they were told to place the VA system without consider other components or sub systems in the vehicle within the restricted area. Each session lasted for approximately 20 minutes.

The concepts generated from both the brainstorming and workshop sessions were summarised in a table. If concepts were very similar, they were merged into one concept. The concepts were evaluated and screened using an elimination matrix. The matrix took demands from the requirement specification into consideration. It was done to ensure that the concepts fulfilled the demands stated in the project. (Almefelt, 2017)

After the elimination matrix, the remaining concepts had to be further evaluated and compared against each other. This to later be able to select a final placement of the induction plate in the vehicle. In this further development stage, these concepts were evaluated based on their positions in the design space of the vehicle and visualised in a figure. The concepts which were located in the same area were clustered together and divided into different sections. These sections then laid the foundation for the further evaluation and elimination of placement ideas of the VA. This way, it was easier to only focus on the positioning and not on the concepts itself. It was also realised that a decision for the placement of the VA could be taken without choosing a specific geometry concept at that stage. However, the concepts were not forgotten, only put on hold. When a final positioning of the VA was determined, the concepts involving that section were brought back into the development process in later phases.

When the concepts had been divided into sections, rough CAD models of the VA were made in the CAD software Catia V5. This to further examine how the VA could fit within the different sections. Since no decision about what coil design to use was taken at that time, models for the Circular as well as the Double D were built. The dimensions used were taken from the standard SAE J2954. The CAD models were then inserted into the platform model to get a visualisation of how the models could fit within the different sections without inflicting with, for instance, the ground clearance. The ground clearance was visible in the CAD model of the platform as structure planes.

When the models of the VA had been evaluated regarding positioning in all the section, a concept screening matrix was utilised. In this case, the sections were compared against each other, not the concepts. This way, the most promising sections could be selected for the further development process. The result from concept screening matrix is presented in form of tables. From the concept screening matrix and further evaluation, as well as consultation with experts at Volvo Cars, one section where the VA should be positioned was determined.

6.2 Design Space Evaluation and Determination

The nine zones of the car together with their names can be found in Figure 6.1. The dashed lines indicate each zone, and their colour the decision whether to investigate them further or eliminate them. Green colour symbolises the zones which will be further analysed compared to the red ones, which were eliminated. The decision about which zones to eliminate was taken with the so far gained knowledge. The pros and cons lists made took for instance the positioning over GA, distances to driver and passengers, as well as collision protection into consideration. The pros and cons lists can be found in Appendix C.

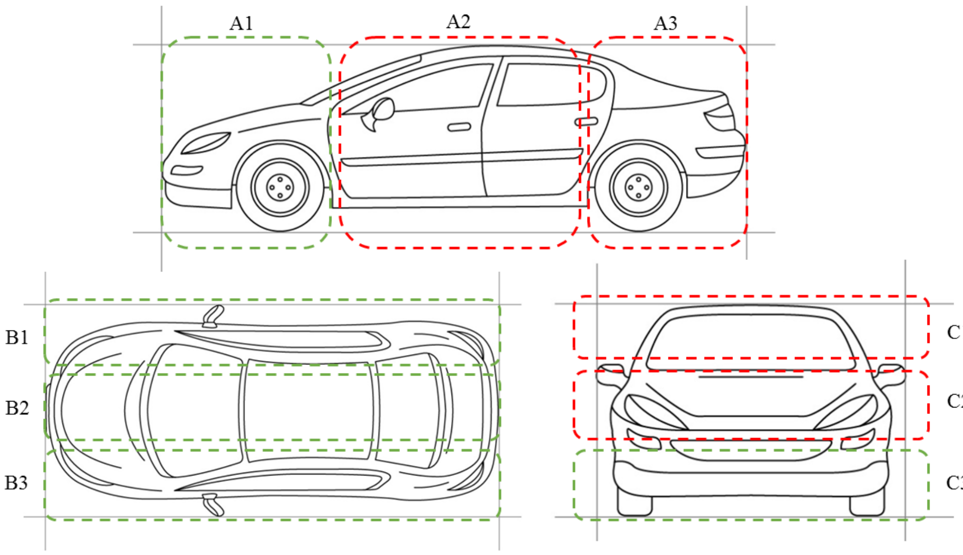


Figure 6.1: The division of a traditional car into nine zones. Picture retrieved and modified from Freepik.

Regarding A, only one zone remained after elimination, A1. The positioning and predicted standard in the market analysis were critical for zone A3. From the market analysis, it was found that only one competitor places their VA in the rear part of the vehicle. This could imply that a possible standard of the placement will be somewhere in the zones A1 and A2. Together with these aspects, it was considered to be difficult for the driver to park so that the VA will be located near the GA, compared to if it was positioning in zone A1. These aspects resulted in an elimination of zone A3. Further, the evaluation with employees at the company resulted in an elimination of zone A2. The reason was the lack of space in the updated SPA platform. Critical components in form of batteries were placed in the zone which could not be modified. However, zone A1 was considered to have great potential due to the prediction of standard, ease to manoeuvre the car and the long distance from VA to driver and passengers which provides possibilities to protect the driver and passengers from magnetic fields.

When considering the zones of B, all zones remained for further development. The pros and cons list indicated B2 as the most promising position. The position provided protection in collision together with the ease of parking. However, the cons for B1 and B3 were considered being too minor for elimination in this early stage of the process. For instance, it could be of advantage to position the components which accomplish the wireless connection between VA and GA in the centre in the transverse direction. However, other components, such as the rectifier, could possibly instead be placed on one of the sides.

Regarding perspective C, only one zone remained after the screening. Zone C1 was eliminated due to the short distance between the VA and the driver and passengers together with problems of the installation of GA. The short distance could result in problems to protect human beings from the magnetic field generated by the wireless charging system. Considering the complete system, also the placement of GA could be a problem. This since the GA needs to be placed close to the VA. This would probably not be a problem in a garage, but could be problematic at an outdoor parking spot. The GA will be needed to be installed on some sort of arrangement instead of just placing it on the ground. Same kind of problems occur when analysing zone C2, which also was eliminated at this stage. Zone C3 remained for further development since it was considered having great potential regarding attachment possibilities, connection to GA and the long distance to driver and passengers which provide possibilities of protection against magnetic fields.

In conclusion, the design space of the vehicle determined which was up for the concept development can be seen in Figure 6.2. The dashed green zone represents the design space which includes the zones A1, B1, B2, B3 and C3. This design space was then used when generating concepts concerning the position of the VA.

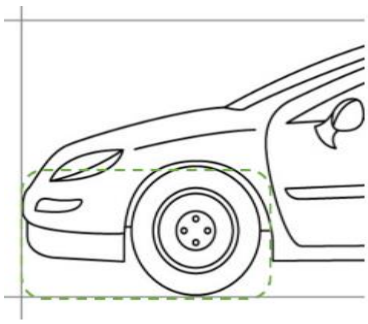


Figure 6.2: Space chosen where the VA should be placed. Picture retrieved and modified from Freepik.

6.3 Early Concept Development of VA Positioning

The individual brainstorming resulted in 16 concepts. The concepts included a wide range of ideas concerning positioning of the VA. Ideas such as placing the VA in the wheels or on the rims occurred, as well as a solution regarding location in the registration plate. Together with these concepts, modification of battery components, sub frame and the cooling system were analysed. The ideas included for instance squeezing and division of components which could create space for the VA. Also, an idea of integrating it in the entire protection cover under the car occurred. Figure 6.3 illustrates some of the concepts generated from the brainstorming.

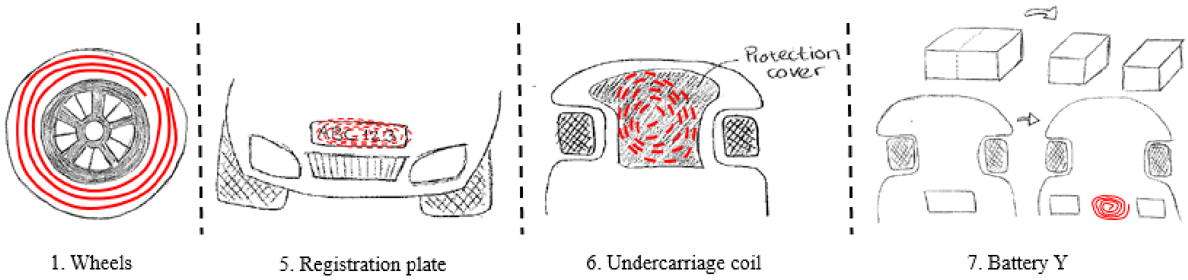


Figure 6.3: Some of the concepts generated from brainstorming.

The workshop with employees at Volvo Cars generated seven concepts. Many concepts were similar to the ones generated in the individual brainstorming session. The participants focused on integration in the front sub frame as well as modification of the cooling system, see Figure 6.4. Concepts of adding an extra cooling system in a space in front of the wheels were generated. The idea was that the extra cooling systems could reduce the volume of the existing system, which could enable space for the VA.

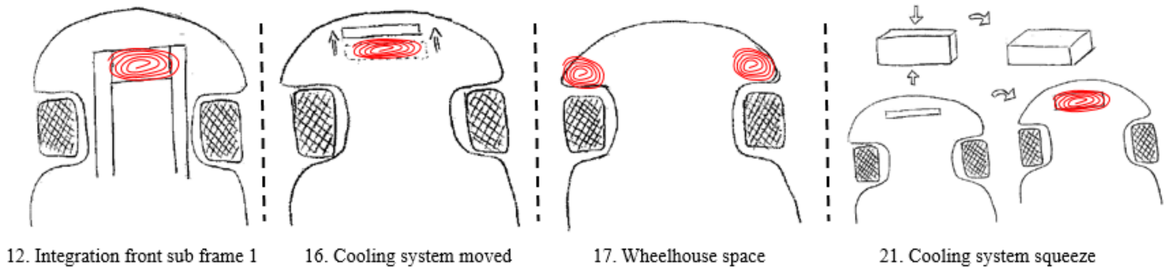


Figure 6.4: Some of the concepts generated from workshop.

When all concepts from both the brainstorming and workshop sessions were summarised, it was realised that some of them were very similar to each other. These concepts were merged into one. This resulted in that 21 unique solutions were found. The summary together with pictures of the concepts can be found in Appendix D. All concepts were evaluated using an elimination matrix. The elimination matrix was used to ensure that the positioning chosen would fulfil the demands from the requirement specification, see Appendix B1. In Table 6.1, the elimination matrix is shown excluding comments on each concepts. The entire matrix however, can be found in Appendix E.

Table 6.1: Elimination matrix for the early concept development of positioning.

	Demands / Concepts	Coil design fit into geometry	Compatible with GA	Collision - deformation	Modification of critical part	Distance to GA	Ground clearance	Compatible with critical vehicle components	Further Development
1	Wheels	+	-						No
2	Rims	+	+	+	+	-			No
3	Air gap turner	+	+	?	+	+	+	-	No
4	VA locates GA	?	+	+	+	+	+	+	Yes
5	Registration plate	-							No
6	Undercarriage coil	+	-						No
7	Battery Y	?	+	+	?	+	+	?	Yes
8	Battery Z	?	+	+	?	+	+	?	Yes
9	Battery X	?	+	+	?	+	+	?	Yes
10	Gap protection cover	?	+	+	+	+	?	-	No
11	Below front sub frame	?	+	+	+	+	+	?	Yes
12	Integration front sub frame 1	?	+	?	?	+	+	+	Yes
13	Below front undershield	?	+	-					No
14	Front side gap	?	+	-					No
15	Cooling system split	?	+	?	-				No
16	Cooling system moved	?	+	?	-				No
17	Wheelhouse space	-							No
18	Integration front sub frame 2	?	+	?	?	+	+	+	Yes
19	Extra cooling systems	?	+	?	-				No
20	Above front sub frame	?	?	+	+	-			No
21	Cooling system squeeze	?	+	?	?	+	+	?	Yes

The elimination matrix reduced the number from 21 to 8 concepts. The concepts regarding placement in the wheels and on the rim were eliminated due to problems with the GA concerning compatibility and distances. The variation of the width of the car was one reason for the problems. Also, the position in the registration plate was eliminated. The reason was the limited space the plate allowed which not would be enough for the coil design. The solution of placing the VA in the whole undercarriage coil were eliminated since the concept would be very unique for Volvo, and therefore difficult to make compatible with GA.

Only one concept regarding modifications and positioning of the existing cooling system remained after the elimination. Consultation with employees indicated that the air flow was approximately 75 % lower on the sides in the front compared to the middle part of it. The concepts eliminated would result in too low air flow into the cooling system which would affect the entire system too much. The solution of adding extra cooling systems in front of the wheels was considered to not be enough effective to replace the entire cooling system, or reduce the volume of the existing system to a sufficient level. However, a concept of squeezing the cooling system in z direction was still left for further analysis. This since it still could utilise the effective air flow in the middle part of the front.

The solutions regarding modification of the battery component remained after the elimination. The modification would result in consequences for the platform, but the changes were not considered being too critical for elimination in this early stage of the process. Further development and analysis of these concepts were needed together with consultation with experts within the field. Together with the battery ideas, both the concepts regarding integration in the front sub frame remained for further analysis. However, positioning of VA in the gap in the protection cover, the front undershield or above the sub frame were all eliminated. Compatible with critical vehicle parts and deformation in collision were the demands which these concepts could not fulfil. The position over the front sub frame will result in problems regarding the distance to the GA, and that components will block the wireless charging.

Below, the concepts that remained after the elimination for the further development are briefly explained together with a sketch of each concept. The concepts regarding battery and integration in front sub frame are merged in this description due to their similarities.

***VA locates GA*:** This concept is placed below the front sub frame, in front of the motor, see Figure 6.5. The attachments will be on the sub frame. Due to the size of the VA, the component may be needed to be integrated in the sub frame. In that case, the VA could be designed to carry the load needed to not weakening the sub frame structure. The idea in this concept is that when the car is parked, the VA can move in x, y and z direction. The movements will be used to find the GA and connect to it wirelessly. It is then possible to have the most effective charging process as possible.

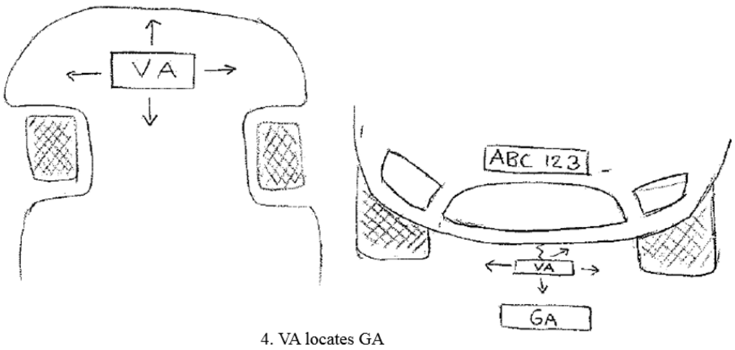


Figure 6.5: Visualisation of the VA locates GA concept.

Battery X, Y, Z: Three concepts are placed in almost the same position, called Battery X, Battery Y and Battery Z. All concepts will be using the space currently occupied by a battery component. This means that they all will include some modifications of this component. In Battery X concept, the battery component is divided in two pieces in x direction. The component is then redesigned so that it gets longer in y direction and thinner in x direction. This enables space in front of the battery component. The concept can be viewed in Figure 6.6. The concept called Battery Y, splits the battery component in y direction into two pieces. These are then pushed out to the sides of the vehicle which enables space in between them for the VA, see Figure 6.6. Finally, Battery Z concept splits the battery into two parts in z direction. The two parts are then placed beside each other, making it longer in y direction which enables space on top of the battery component, see Figure 6.6. The coordinates x, y and z refer to the global coordinate system explained in Section 2.4.

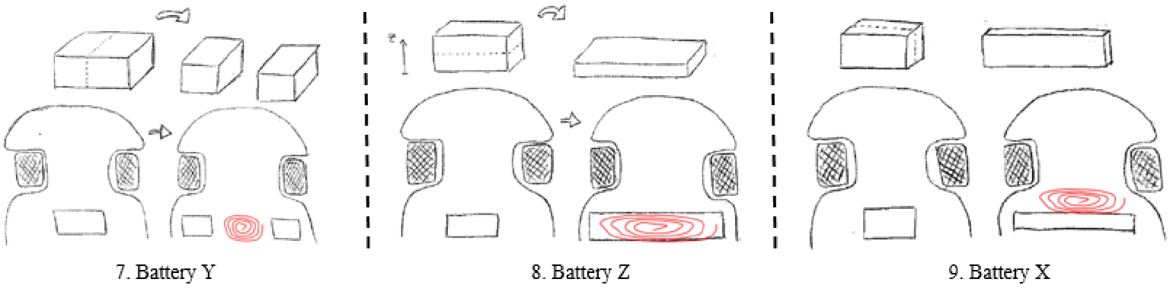
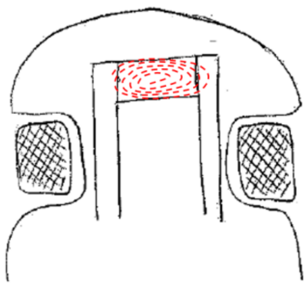


Figure 6.6: Visualisation of the Battery X, Y and Z concepts.

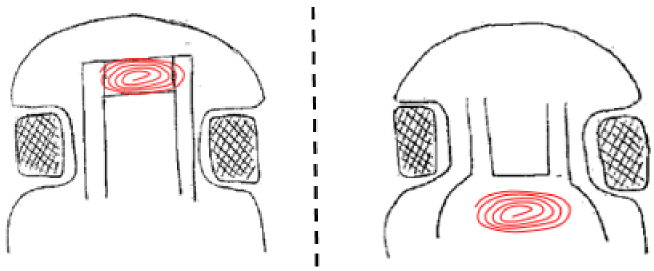
Below front sub frame: The concept is placed below and between parts of the front sub frame, see Figure 6.7. The concept is integrated in the protection cover underneath the car. The integration will result in requirements regarding protection of other components. The space has a small angle which the concept will be designed to fit into. The concept will be placed on the ground clearance.



20. Below front sub frame

Figure 6.7: Visualisation of the Below front sub frame concept.

Integration front sub frame 1 and 2: The concepts are using the front sub frame for attachments. Concept one will be using the front part of the sub frame while the second concept will use the rear part of it. Both concepts are integrated in the sub frame and designed to carry load. The sub frame will in both cases be modified to remain strength. The concepts will be placed on the ground clearance which could result in modifications of the protection cover. The front part of the sub frame where the first concept is located has space for modifications in its surrounding, while the second concept has more restricted design space due to nearby vehicle components. The concepts are visualised in Figure 6.8.



12. Integration front sub frame 1 18. Integration front sub frame 2

Figure 6.8: Visualisation of the Integration front sub frame 1 and 2 concepts.

Cooling system squeeze: This positioning concept is placed in front of the car, below the cooling system, see Figure 6.9. The idea is to create space for the VA by squeezing the cooling system in z direction. This will result in a thicker cooling system in x direction. This will affect the cooling system since the area where the air will cool the water is decreased. Further modifications are therefore needed for the cooling system to keep its efficiency.

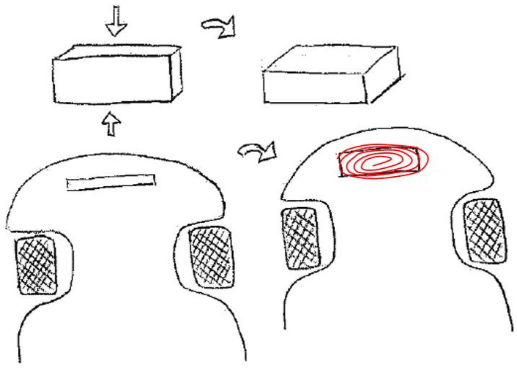


Figure 6.9: Visualisation of the Cooling system squeeze concept.

These eight remaining concepts were then used in the further concept development of VA position. The further concept development phase of the positioning guides how these eight concepts were narrowed down. In the end of this phase, a position of the VA was determined.

6.4 Further Concept Development of VA Positioning

As explained, eight concepts remained after the elimination matrix. The concepts were evaluated based on their positions in the design space of the vehicle. A simplified visualisation of the placement for each concept is shown in Figure 6.10. It is the front of a vehicle with its front wheels that is shown. The numbering in the figure refers to the numbering of the concepts. For complete name and description of concepts, see Appendix D.

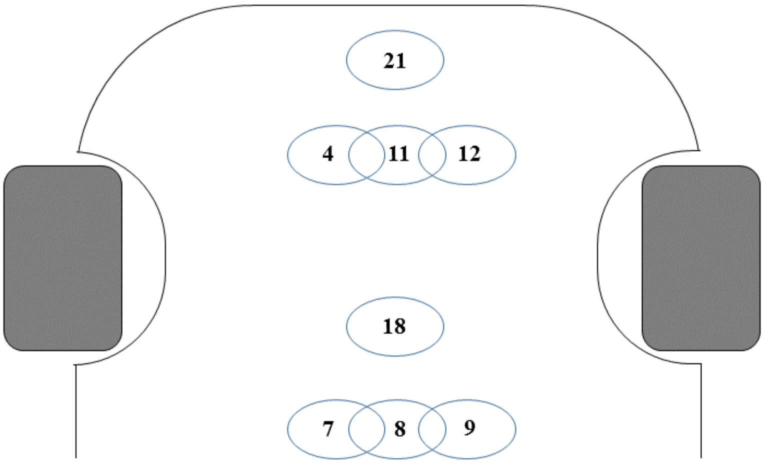


Figure 6.10: Overview of the remaining concepts and their placement in the vehicle.

There are only approximate placements of the concepts in the figure. For instance, concepts 4, 11 and 12 are located at the same position or nearby each other in the vehicle. These concepts have been clustered together in the figure. From this visualisation, it was found that the concepts could be divided into sections. Instead of further evaluating the concepts at this stage, the sections were subject for the evaluation and screening processes. This since it was realised that a decision regarding placement of the VA could be taken without choosing a specific concept. Instead, a section was selected for final placement. This way, several concepts could be utilised in the later development process when more knowledge was acquired and geometry of the VA were more thoroughly determined.

In total, the eight concepts were divided into four sections, see Figure 6.11. The visualisation to left shows how the concepts were divided into the sections, where the sections are represented as blue dashed rectangles. The picture to the right shows the sections with their corresponding names.

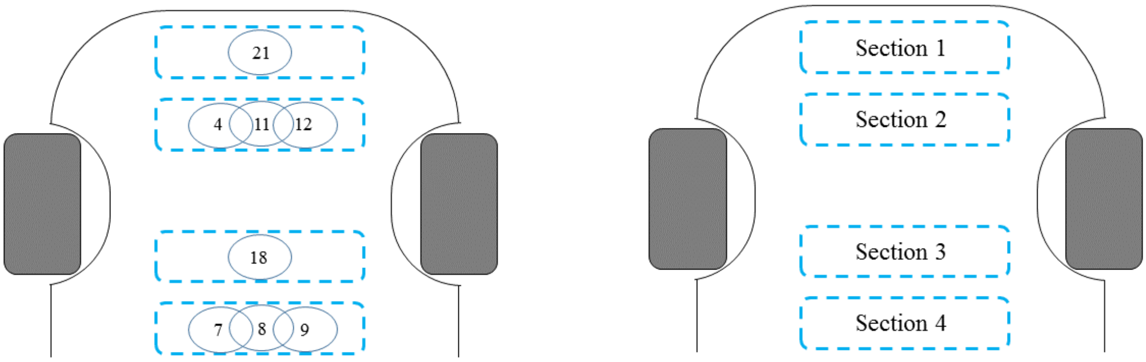


Figure 6.11: Visualisation of how the concepts were divided into sections.

Section 1 is the area mainly where the cooling system is located currently. Sections 2 and 3 are located on different locations on the front sub frame, while section 4 is located where the battery component is placed. When the concepts had been divided into the four sections, these sections were evaluated based on the feasibility of position the VA within these areas.

The rough CAD models of coil houses made for evaluation were dimensioned according to the standard SAE J2954. As explained, no decision of coil design was made yet. Therefore, both a Circular and DD coil design was modelled. The CAD models are found in Figure 6.12.

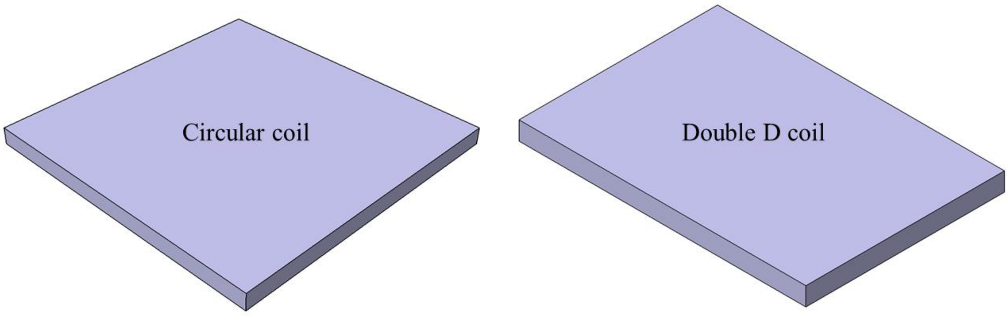


Figure 6.12: CAD models of the two different coil houses.

The coil ground clearance class used was Z2. Only volume of the coils and ferrites together with housing were included in the volume. The volumes of, for instance, electronic components were excluded. This since the more specific design of the VA was developed in the later concept development phase. The dimensions of the CAD models made are shown in Table 6.2.

Table 6.2: Dimensions of the two different coil houses.

Circular coil topology	350 x 350 x 20 mm
Double D coil topology	390 x 270 x 25 mm

When the CAD models had been inserted into the platform, the volumes of the VA was tested around with. The Circular coil design has a quadratic area, while the DD coil design is more of a rectangle. Therefore, the DD was rotated in the platform to find best placement. It was decided to use ground clearance within the 60 cluster of a low model (S60/V60). This because the ground clearance of a low vehicle is stricter which could be more demanding and challenging when finding the position of the VA. If a proper placement could be found in a lower vehicle, it may be more likely to be fitted in higher vehicles with respect to ground clearance. However, one must be aware of that a lower coil ground clearance, which is roughly the same as the distance between VA and GA, results in a lower z class. This also means that the area (x and y direction) of the coil decreases for lower coil ground clearance. Therefore, class Z2 was used which corresponds to the ground clearances of a higher Volvo car. This decision was taken because of the likelihood that the VA will fit into higher vehicles increased even more.

When evaluating and screening out sections, concept screening matrices were utilised. This to be able to compare how well the sections stood against each other for different criteria. Two iterations of concept screening matrices were needed to be able to eliminating sections. The first iteration of the concept screening matrix is shown in Table 6.3.

Table 6.3: First concept screening matrix.

Concept screening matrix - First iteration				
Criteria	**Section 4**	**Section 1**	**Section 2**	**Section 3**
No need for modification of parts	R	0	+	+
Multiple attachment possibilities	e	0	+	+
Low affect of vehicle deformation	f	-	0	0
Many possibilities to protect VA	e	-	0	0
Large distance to "magnetic/electric" component	r	+	+	+
Ease to reach VA	e	0	0	0
Ease to reach vehicle components	n	0	+	+
Ease to park/manoeuvre the car	c	+	+	0
Low cost for modifications	e	0	+	+
Sum +	0	2	6	5
Sum 0	0	6	4	5
Sum -	0	2	0	0
Net value	0	0	6	5
Ranking	**3**	**3**	**1**	**2**

The section randomly determined to be the reference was section 4. In the table, the criteria can be seen on which the comparison was based. In total, nine criteria were used. Some of them were taken from the requirement specification (see Appendix B1), and some since they were of interest in this comparison. In the following, the criteria are briefly explained.

No need for modification of parts: Low or no need for modifications of components or sub systems in the vehicle are necessary to fit the VA.

Multiple attachment possibilities: Great possibilities of installing and attaching the VA in surrounding environment.

Low affect of vehicle deformation: A vehicle is constructed to be able to deform in a certain manner in a crash. This could be different deformation zones and beams. This criterion examines if a section could affect this deformation. A low affect of the vehicle deformations is prefarable.

Many possibilities to protect VA: The possibilities to protect the VA in a collision.

Large distance to "magnetic/electric" components: Surrounding components could affect the function of the VA negatively, and the VA could at the same time affect the surroundings negatively. A large distance to critical components minimises the risk of these noises.

Ease to reach VA: The ease of reaching the VA for installation and maintainence.

Ease to reach vehicle components: The ease of reaching surrounding components for installation and maintainence.

Ease to park/manoeuvre the car: Different locations of the VA could affect how easy it is to make it end up close to the GA.

Low cost for modifications: The cost for the modification of parts due to the placement of the VA, where a low cost is prefarable.

From the first concept screening matrix seen in Table 6.3, it was evident that sections 2 and 3 stood better in the comparison to the reference (section 4) based on the criteria. These section performed similarly in the comparison. Section 2 only received one more point than section 3. Although, sections 1 and 4 received quite lower scores, it was not enough to eliminate them yet. Also, from this concept screening matrix, it could not be decided which section was the best to place the VA. Therefore, another concept screening matrix was performed.

In Table 6.4, the second concept screening matrix is visualised. This time, the section that received highest score from the first concept screening was decided to be the reference. By doing this, it could be seen if this section still was the best when compared to the other sections.

Table 6.4: Second concept screening matrix.

Concept screening matrix - Second iteration				
Criteria	**Section 2**	**Section 1**	**Section 3**	**Section 4**
No need for modification of parts	R	-	0	-
Multiple attachment possibilities	e	-	+	-
Low affect of vehicle deformation	f	-	0	0
Many possibilities to protect VA	e	-	0	0
Large distance to "magnetic/electric" component	r	0	0	-
Ease to reach VA	e	0	0	0
Ease to reach vehicle components	n	0	0	-
Ease to park/manoeuvre the car	c	0	-	-
Low cost for modifications	e	-	-	-
Sum +	0	0	1	0
Sum 0	0	4	6	3
Sum -	0	5	2	6
Net value	0	-5	-1	-6
Ranking	**1**	**3**	**2**	**4**

The result from the concept screening matrix shows that section 2 still got the highest score. Again, section 3 received second highest score, only one from section 2. It can also be seen that sections 1 and 4 received lower scores. Based on these concept screening matrices and evaluation of the feasibility of positioning the VA in these sections, it was decided to eliminate sections 1 and 4. This also meant that concepts 7, 8, 9 and 21 were eliminated from the further development process.

However, it was still not evident which of the sections 2 and 3 to select as final placement from the concept screening matrices. Both these placement sections concerned the front sub frame of the vehicle. Therefore, further evaluation was needed where the front sub frame was in focus. By examining the platform even more and consulting with experts at Volvo, a final decision was made.

Section 3 was selected as the final section of positioning even though it was not ranked highest in the concept screening matrices. This automatically resulted in that concept 18 was selected while concepts 4, 11 and 12 were eliminated. However, exactly this concept was not needed to be the final concept. In the next concept development phase, the geometry and functions of the component were more thoroughly determined, which could result in that ideas from already eliminated concepts were raised again. According to experts at Volvo Cars, the distance from the front of the vehicle at the registration plate to the VA have to be at least 700-1 000 mm. This due to EMC. If placing the VA in section 2, this distance would approximately only be 450 mm. At this time in the selection process, the ground clearance to use was determined. It was decided that the ground clearance for cluster 60 low vehicle. This since this cluster had most demanding requirements on the ground clearance. However, with this ground clearance, more possible space within the section 3 compared to section 2 seemed to be available. This space could be utilised for the placement of the VA.

6.5 Summary of Concept Development Positioning

A vehicle was screened to identify the best possible positioning. The vehicle was divided into zones where the bottom front was selected for further development based on evaluations. Concepts were generated with a 3D model of the platform and the restricted area. The concepts were evaluated and eliminated until only a few remained. The concepts left were divided into sections which later were evaluated using two concept screening matrices and demands from the requirement specification.

The selected section for further development of the VA was in the rear end of the front sub frame. The area was considered to have potential for integration and modifications of the VA and the sub frame. The area was considered to deliver a better customer experience due to the ease to manoeuvre the front part of the car. The selected positioning is similar to some of the competitors, such as Audi, BMW and Mercedes-Benz.

7 Geometry Concept Development

This chapter concerns the concept development of the geometry of the VA, and it is divided into two parts; the determination of inner constraints and the actual concept development of VA geometry. Since the position of the coil housing was determined in the previous chapter, the placement of the electronic parts of the VA will be determined here. The section about inner constraints describes how different decisions were taken before the actual concept generation of the geometry was initiated.

7.1 Determination of Inner Constraints

The inner constraints needed to be determined before the concept development phase were which coil design to use and the design space for the electronics. Also, an investigation of the platform was undertaken to be able to figure out if any already existing component could be utilised in the performance of the VA. Below, the strategy to be able to make these decisions is explained. This is then followed by the results and the determinations.

7.1.1 Inner Constraints Determination Strategy

As described in the technology benchmarking (see Section 4.2.3), there are generally two coil designs on the market. Both designs are patented and the intellectual properties must be bought or licensed to be able to use the designs. An evaluation of each coil topology was needed to understand which technology that would be most appropriate to use for the concept under development. Both topologies were investigated to gain more knowledge to be able to compare them against each other based on several criteria. The criteria were based on the requirement specification. Based on the comparison and evaluation, one coil design was decided to be used for the VA. Depending on coil design, the volume of the design was determined based on WPT and Z class using the SAE J2954 standard.

When the coil design was decided, the volume needed for the electronics in the VA was determined. As described in Chapter 5, the VA system needs electronics for communication and control. A rectifier is required to convert AC to DC. The conversion is required due to the batteries' ability to store energy. Due to limited knowledge about electrification, a fixed volume of the electric equipment was determined. The volume was determined by evaluation loops, both within the project group and with electronic experts at Volvo Cars. However, the fixed volume was used as a guidance for further development of concepts. This means that ideas to decrease the volume was still up for development.

In order to be able to decrease the volume of the electronics, integration with other vehicle components could be suitable. This integration means that other components' functions could be utilised in the performance of the VA. First, all components and functions needed for the electronics in the VA were defined and investigated more thoroughly. This resulted in a list containing these components. This was both based on the early investigation in the functional description, see Section 5.1, and a bill of material received from Volvo. Then, through discussions with colleagues, vehicle components were examined to figure out if this kind of integration could be feasible.

7.1.2 Coil Topology Determination

The results from the research about coil design were summarised in a comparison matrix, see Table 7.1. Both topologies are visualised in Figure 7.1. The table shows that the Double D topology was to prefer with the positioning in consideration. The research about the topologies showed that the Circular coil was the simplest to manufacture. It is symmetric and can have a circular as well as a rectangular shape. The design allows a good rotational tolerance, which means that the car can approach the GA in any direction without having problems with charging process efficiency. On the other side, the design was sensitive to offset in x, y, or z direction. If parked misaligned with 40 % in any direction, the coupling factor falls to zero. (Covic & Boys, 2013).

Table 7.1: Comparison between Circular and Double D coil topologies.

Criteria	***Circular***	***Double D***
Offset x direction	-	+
Offset y direction	-	+
Offset z direction	-	+
Rotational tolerance	+	-
Manufacturability	+	-
Fit into front sub frame	-	+
Coupling factor	-	+
Sum +	2	6
Sum 0	0	0
Sum -	6	2
Tot	-4	4

The Double D topology was much better when it comes to manage misalignments in x, y and z direction (Alatalo, 2015). The complexity of the topology results in higher manufacturing cost compared to the Circular topology. The selected placement of the coil house in the front sub frame is having a rectangular shape which makes the Double D topology more appropriate in this position. Also, the coupling factor which indicates the efficiency of the charging process is higher on the Double D topology. (Budhia et al., 2013)

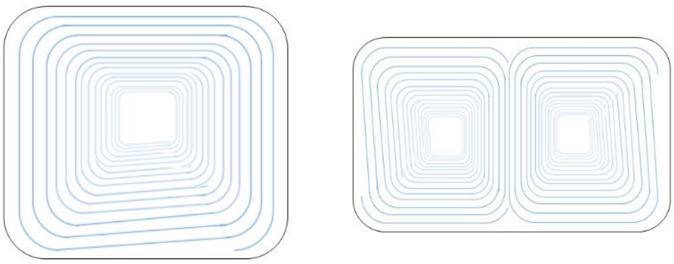


Figure 7.1: Visualisation of Circular and Double D coil topologies.

The results from Table 7.1 indicate that the Double D topology is to prefer with the given conditions. The offset in x and y direction were considered to be of more importance compared to the rotational and z directional tolerance due to the restricted area in a garage or parking lot. A rotational offset of the car within the area was considered to be less likely to occur compared to misalignments in x and y directions. Offset in z direction was considered being even more unlikely to occur. The research showed that both topologies can be manufactured, but the Circular one is easier. However, the knowledge that both are possible to manufacture was considered to be enough for further development of the Double D topology. Finally, the geometry's fit into the selected position in the platform as well as the coupling factor were crucial for select the Double D topology for the further concept development of the VA.

Due to the decision to utilise the Double D topology as coil design, the volume of the coil could be determined. In the standard SAE J2954, there are guidelines of volume needed for different coil designs, Z classes and power input. As mentioned, it was decided to use the class Z2. In the requirement specification, it was stated to use 11 kW as power input. In the standard, 11 kW is represented as WPT3 (wireless power transfer, class 3). The volume needed which includes coil, ferrite and coil housing is

$$Volume_{ferrite,coil,housing} = 270 \cdot 390 \cdot 25 = 2\ 632\ 500\ mm^3 \approx 2.6\ dm^3$$

This volume is according to the standard necessary to fit the coil design needed for the VA under development, and to be compatible with the GA in the standard. Therefore, an assumption was made that this volume was fixed and could not be optimised during the forthcoming development.

7.1.3 Electronic Design Space

The evaluation with experts within electricity resulted in a fixed volume of 1.9 dm^3 for the electronic equipment. Based on the standard SAE J2954, coil, ferrites and housing for an 11 kW charger with coil ground clearance Z2 has the dimensions of 270 x 390 x 25 mm. A volume of 2.6 dm^3 is thereby reached. This means that if the area in x and y direction is kept also for the electronics, the entire VA will have a total thickness of 43 mm. In Equation 1-4, the calculations for the total thickness are done.

$$Volume_{ferrite,coil,housing} = 270 \cdot 390 \cdot 25 = 2\ 632\ 500\ mm^3 \approx 2.6\ dm^3 \tag{1}$$

$$Volume_{electronics} = 1\ 900\ 000\ mm^3 = 1.9\ dm^3 \tag{2}$$

$$t_{electronics} = \frac{1900000}{270 \cdot 390} = 18\ mm \tag{3}$$

$$t_{tot} = 25 + 18 = 43\ mm \tag{4}$$

Where $t_{electronics}$ is the thickness or height of the electronics volume and t_{tot} is the total thickness of the VA excluding electronics housing. The volume for the electronics was used as guidance for further development to ensure that all electronic equipment fitted within the developed concept. However, the volume was not fixed and ideas for changing the dimensions were still up for development.

7.1.4 Electronic Integration with Vehicle Components

The electronics needed for the VA to work are listed and briefly described below. It is only the electronics needed, for instance, for the communication and control of the VA that are listed. Coil and ferrites are not included since they belong to the volume already determined in Section 7.1.2.

- Rectifier: *Converts AC to DC*
- Cooling system: *Cools the rectifier*
- Low voltage (LV) signal connector: *12 V connectors for communication*
- High voltage (HV) connector: *Connectors for HV*
- Voltage sensor: *Measures the voltage*

- Current sensors: *Measures the current*
- Temperature sensors: *Measures the temperature*
- Electric shield: *Prevents leakage of magnetic field*
- EMC filter: *Prevents reflection of current*
- Control unit secondary: *Controls power level, voltage etc.*
- WLAN: *Wireless communication with other equipment*
- HV cavity insulator: *Foam to fill out cavity*

When the first electronic component, the rectifier, was analysed, an already existing vehicle component found to be of interest, the on-board charger (OBC). An OBC is the component in the car which transforms AC from the plug-in unit to DC before entering the vehicle battery. The feature of the OBC seemed to be feasible to utilise for the VA since they had similar function, only different source of energy. If integrating the VA with the OBC, the rectifier in the VA could be excluded. It was also found that the cooling system could be eliminated when utilising the OBC. This since the transformation from AC to DC will take place in the OBC, and this conversion is the source of heat, see Section 5.1.3. By eliminating the rectifier and the cooling system, the volume of the electronics in the VA could possibly be reduced.

Further, the connectors for low and high voltage were not considered to be feasible to eliminate from the VA. Communication with, for instance, the wall box will always be needed to regulate the charging process. The HV connector will be needed since the produced current needs to be transported to the battery through wires.

The sensors that are measuring the voltage and current had potential to be integrated in the OBC. The OBC is measuring the voltage and current in the plug-in system, which could be utilised also for the wireless charging. However, the temperature sensor seemed to be more critical. This since a protection for overheating the components in the VA is necessary and the sensor that is measuring the temperature needs to be placed close to the coil. A regulation of temperature could be achieved by controlling the effect from the wall box to reach an optimal value. This will be needed even though the rectifier will be eliminated in the VA. The sensor will detect if the VA gets overheated, and communicates to the wireless system that the charging has to be turned off or operate with a lower effect.

The electric shield and EMC filter were crucial for the performance of the charging process, with or without the OBC integration. Both of them need to be integrated in the VA due to the generated magnetic field which needs to be protected for nearby components. No existing component in the car was found to be of interest to complement the secondary control unit, WLAN or HV cavity insulator. Therefore, these components were considered to be needed in the VA.

From this investigation, it was realised that an integration with the OBC had large potential. By integrating the VA with the OBC, the rectifier, cooling system, voltage and current sensors could be eliminated from the VA. This elimination could lead to a reduction of the necessary volume needed for the electronics. A reduction in volume could be beneficial due to, for instance, lower costs and smaller modifications of the platform. This idea to utilise functions of the OBC was then brought to the concept generation and development of the VA.

7.2 Concept Development of VA Geometry

When the inner constraints were set, the actual development of the geometry was initiated. This involved the generation of complete concepts, evaluation and comparison to be able to eliminate concepts, and the selection of a final concept. The complete concepts included the geometry and placement of the electronics, if movement of the VA was possible and if utilising already existing components in the platform. They did also include the coil housing, however, the geometry and positioning of this was determined in Chapter 6. In the following, the strategy for undertaking the generation, screening and selection is described. Then, the results of these steps are presented.

7.2.1 Strategy for Concept Development of VA Geometry

With the inner constraints in mind, the actual development of the geometry was initiated. The process focused on the shape, movements and number of boxes, as well as integration with other vehicle components. This also included the placement of the electronics of the VA in the platform. Ideas about how the electronics could be positioned were generated with the fixed positioning of the coil house in mind.

Before complete concepts were generated, concepts of different sub functions/components were first generated. These could then be combined into different concepts by using morphological matrix. Two morphological matrices were established, one for single box solutions, and one for multiple box solutions. Single box solutions had the electronics integrated in the coil house unit, while the multiple box solutions had one or multiple boxes for the electronics separated from the coil house. The concepts were combined with different shapes of electronics volume, z movement and integration with the existing component OBC. It was not necessary that all concepts included a z movement or integration of the OBC.

Ideas of the geometry of the electronics were generated by using braindrawing and CAD modelling. These ideas were then inserted to the morphological matrices. Braindrawing is similar to brainstorming, but only sketches are used to present ideas (Wiberg Nilsson, Ericsson & Törlind, 2015). Each participant sketched ideas of the geometry on a paper. After five minutes, the participants switched places and continued working with the paper in front of them. It was then possible to get inspiration from others but also build upon others ideas. The braindrawing was executed by the project group. Then, all ideas were summarised and concretised. CAD models were made of the concepts, which thereafter were modified to fit within the selected positioning. The advantage of drawing CAD models was that these models could be inserted and positioned into the platform directly. In this way, it was easy to make modifications to better fit in the platform.

The idea of having a movement of the VA in z direction emerged already in the previous chapter, see Chapter 6. A movement in height will result in a smaller distance between the GA and VA during the charging. This could result in higher charging efficiency and decreased dimensions of the coil design. However, it was not yet decided whether to include such a movement or not, but the idea had potential and was further investigated. Ideas of different movement solutions were generated by a brainstorming session within the project group. Then, these movement ideas were put into the morphological matrix.

From the morphological matrices, several concepts were generated. After this generation phase, evaluation of the concept took place. The evaluation was initiated with a discussion with a responsible person for the sub frame at Volvo Cars. The objective of the discussion was to discover and understand where modifications of the sub frame could be more or less critical. Based on this discussion, concepts that did not seem to be feasible without interfere with critical parts of the sub frame were eliminated. This also resulted in some modifications of concepts to still have the opportunities to be realised. The remaining concepts were then compared against each other in concept screening matrices. Two iterations of concept screening were necessary to be able to eliminate the number of concepts. When only a few concepts remained, these were further evaluated and later combined to finally result in one most promising concept.

7.2.2 Concept Generation of VA Geometry

Ideas generated for the geometry together with placement of cooling system are presented below, see Figure 7.2. The housing for the coil and ferrites is represented in red colour, the electronic equipment in blue and the cooling system in yellow. The concepts were generated with the integration of the sub frame in mind, with the goal of minimising the need of modifications of the sub frame as far as possible.

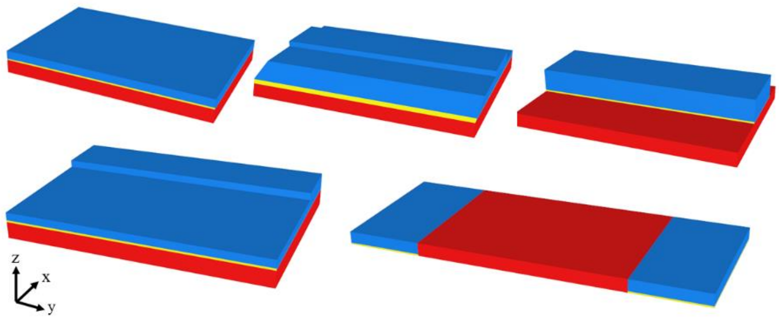


Figure 7.2: Different ideas of the VA geometry including cooling system.

Figure 7.2 illustrates ideas generated of how the movement of VA could be utilised. All ideas generated are dependent on a mechanical control and need electronics to work, for instance, an electric motor. The idea furthest to the left, M1, works like an accordion. The joints, illustrated with circles, makes the VA move in z direction. Next, an idea of having a half accordion is presented. The idea works in the same way as the previous, but it only has two joints and two rods.

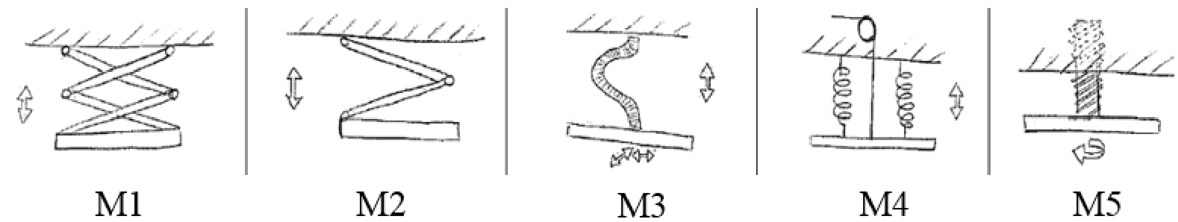


Figure 7.3: Different ideas of the movement in height of the VA.

The third illustration of a principle to accomplish a change in position in z direction was inspired by a lamp holder. The hose is made of flexible rings, and can be moved in both x, y, and z direction. In the fourth idea illustrated, M4, two springs and one small wheel is used. A wire is wrapped around the wheel and connected to a small motor to control the position of the VA. The last illustration, M5, shows a rotating idea inspired by a screw. The entire VA will be turned while changing position in z direction.

All ideas were summarised in morphological matrices. One matrix for single box solutions and one for multiple box solutions, see Appendix F. The ideas were combined to develop total concepts. In total, 18 rough concepts were generated. However, after evaluation and discussions, eight concepts remained. These concepts are presented below. The concepts are divided into single or multiple box solutions.

7.2.2.1 Single Box Solutions

In the following, concepts including one box will be presented. Single box solution means that the electronic equipment is placed in the same unit as the coil house. A description of the shape, cooling system as well as movement and integration with OBC for each concept will be presented for each concept. Complementary to the description, each concept is illustrated with CAD models.

The Sandwich

The concept has a rectangular shape according to the standardised shape of the coil house in the recommended practice SAE J2954. The electronic equipment is placed over the VA with the same dimensions as the coil house in x and y direction. The cooling system is placed between the coil house and the electronics. The concept is only integrated and attached to the sub frame. The Sandwich has a movement in z direction. The movement starts when the GA and VA are aligned and the charging process initiates. The movement is realised by the movement idea M1 which includes rods and joints. Mechanical control of the movement system is needed, as well as electronics. The concept can be found in Figure 7.4. The movement idea is visualised in green.

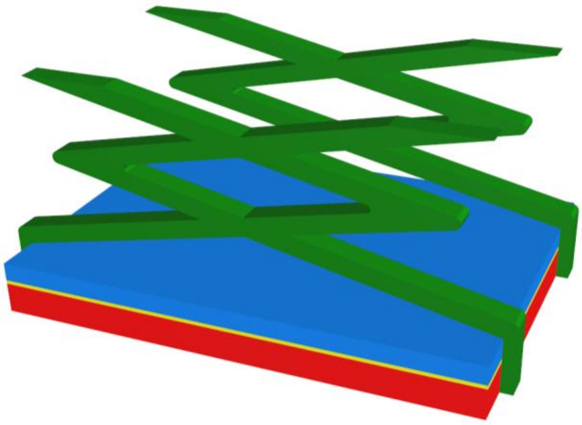


Figure 7.4: The Sandwich concept.

The Podium

The concept is only integrated in the sub frame. All electronic equipment is placed in a box over the coil house. The box is designed to minimise the need for modifications of the sub frame. The VA is fixed and attached to the sub frame. An integration with the OBC is included which eliminates the need for a rectifier and a cooling system. The integration results in a decreased volume of the electronic equipment. The Podium concept is visualised in Figure 7.5.

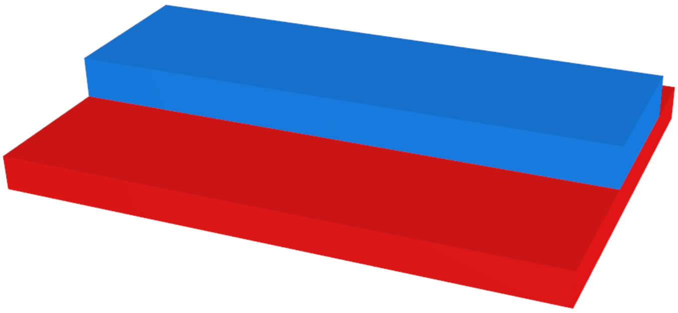


Figure 7.5: The Podium concept.

The Fly

In the Fly concept, all electronics are placed on the both sides of the coil house, see Figure 7.6. The height (z direction) of the electronic volume is the same as for the coil house, while the dimensions in x and y differ. The concept is integrated in the OBC to reduce the need of the rectifier and cooling system, which decreases the volume. The concept is designed to reduce the need for modifications of the sub frame in z direction. However, the Fly is fixed and attached to the sub frame.

Figure 7.6: The Fly concept.

The Ladder

The electronics are placed in a box over the VA in the Ladder concept. The box has a geometry which follows the cavity of the sub frame. The front of the VA has a triangular shape due to the movement of the electric motor. The cooling system is placed between the coil house and the electronic equipment. The concept has a movement in z direction to decrease the distance between the VA and GA while charging. The change in z direction is realised with movement concept M3. The Ladder concept can be found in Figure 7.7.

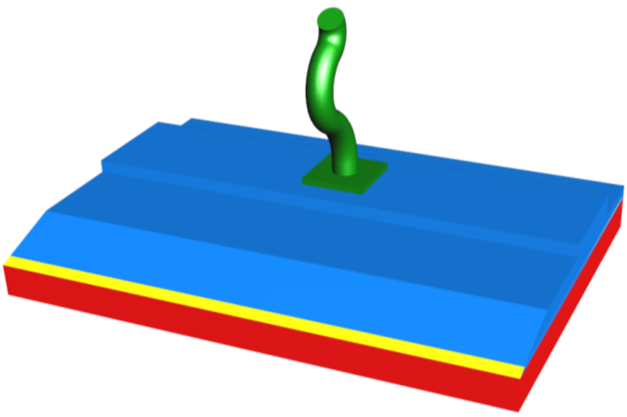


Figure 7.7: The Ladder concept.

7.2.2.2 Multiple Box Solutions

In the following, concepts that consist of multiple boxes are presented. The coil house will always be positioned at the selected position. However, the electronics are separated and positioned at different locations in the vehicle.

The Pool

The concept consists of two boxes, which means that the coil and the electronics are separated. The coil house is integrated in the sub frame at the selected position, see Chapter 6. The electronics are positioned below the sub frame, in front of the engine. The both boxes are connected for control and communication with the GA and other vehicle components. The concept can be found in Figure 7.8.

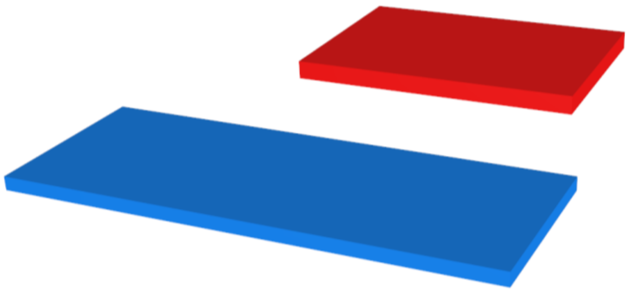


Figure 7.8: The Pool concept.

The Snake

The concept consists of two boxes. The coil house is placed at the selected position, while the electronics are placed below a battery component, behind the coil house. The box for the electronics is fixed and attached to the battery suspension. The coil house has a movement in z direction realised by the movement concept M2. The OBC is integrated in the concept which eliminates the need for cooling. The concept can be found in Figure 7.9.

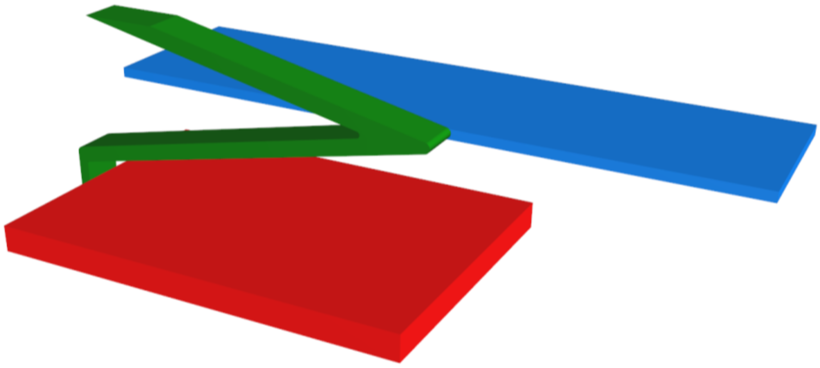


Figure 7.9: The Snake concept.

The Swing

The concept is similar to the Pool concept. It consists of two boxes, one for the coil house and one for the electronics. The box for electronics is placed in front of the motor, over the sub frame. The box is shaped to fit within the cavity between the sub frame and other components. The coil house has a movement in z direction while charging which are realised with movement concept M1. The concept can be found in Figure 7.10.

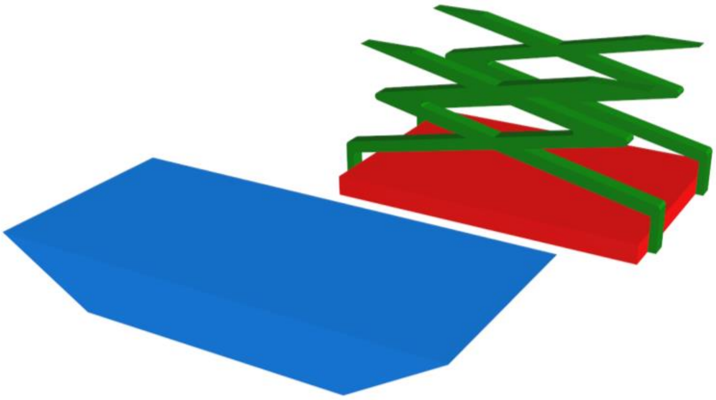


Figure 7.10: The Swing concept.

The Robot

The concept consists of three boxes, one for the coil house and two for the electronics. The coil house is fixed in its position. The two boxes for the electronics are located between the motor and the wheels, on the sub frame. Due to the limited available space there, integration with the OBC is needed to decrease the volume. Also, some modifications of the sub frame are needed to fit with the ground clearance. The concept is shown in Figure 7.11.

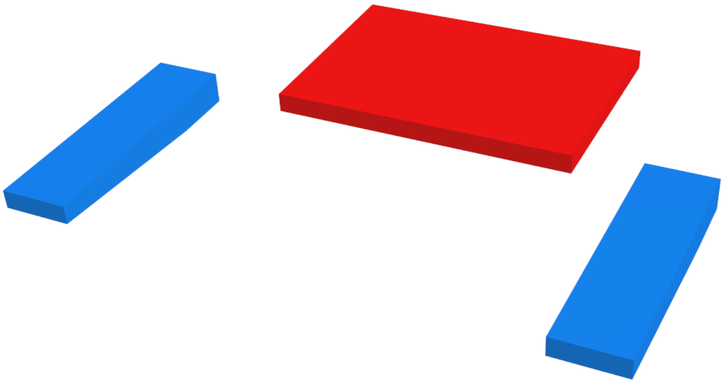


Figure 7.11: The Robot concept.

7.2.3 Concept Evaluation of VA Geometry

The concepts generated were evaluated by using two concept screening matrices and discussions with employees at Volvo Cars with knowledge within the development of the sub frame as well as electronics. The concepts were evaluated and changed during the evaluation process to finally reach an optimal solution. The section is divided into early, later and final evaluation of VA geometry.

7.2.3.1 Early Evaluation of VA Geometry

First, a concept screening matrix was used. This to be able to compare how well the concepts performed compared each other for different criteria. The concept screening matrix can be found in Table 7.2.

Table 7.2: Comparison of concepts in first concept screening matrix.

Concept screening matrix 1 - Geometry								
Criteria	Snake	Sandwich	Podium	Fly	Ladder	Pool	Swing	Robot
Few critical modfications of vehicle components	Reference	+	+	+	+	+	+	0
Multiple attachment possibilities		+	+	+	-	+	+	+
Many possibilities to protect VA		0	0	0	0	-	-	-
Ease to mount VA		+	+	+	+	0	0	-
Low number of parts		-	+	+	-	-	-	0
Long life time		0	+	+	-	+	0	+
High wireless charging efficiency		0	-	-	0	-	0	-
Sum +	0	3	5	5	2	3	2	2
Sum 0	0	3	1	1	1	1	3	2
Sum -	0	1	1	1	3	3	2	3
Net value	0	2	4	4	-1	0	0	-1
Ranking	**3**	**2**	**1**	**1**	**4**	**3**	**3**	**4**

The concept randomly selected to be the reference was the Snake. In the table, the criteria can be seen on which the comparison was based. In total, seven criteria were used. Some of them were taken from the requirement specification (see Appendix B1), and some since they were of interest in this comparison. Below, the criteria are briefly explained.

Few critical modifications of vehicle components: Low or no need for modifications of critical components or sub systems in the vehicle are necessary to fit the concept.

Multiple attachment possibilities: Great possibilities of installing and attaching the concept in surrounding environment.

Many possibilities to protect VA: The possibilities to protect the concept in a collision.

Ease to mount VA: The ease and time to mount the concept when installing the component.

Low number of parts: The number of parts included in the concept. Parts counted were cooling system, rectifier, mechanical structure for movement and number of boxes.

Long life time: The life time of the concepts, for instance, complex functions could result in shorter life time.

High wireless charging efficiency: The efficiency reached when using the wireless charging process of the concept.

The concept screening matrix seen in Table 7.2 highlights the Podium and the Fly as the most promising concepts in comparison to the Snake based on the criteria. It can also be seen that the Ladder and the Robot had the lowest scores. The matrix shows that a high number of boxes is not to prefer since it increases the number of parts and the time for installation. A placement in front of the selected location for the coil housing, see Chapter 6, results in problems in protection. However, the movement increased the charging process efficiency, but also the complexity of the system. The two most promising concepts from the first concept screening matrix had a minus on the criteria *High wireless charging efficiency*. Discussions with employees at Volvo Cars within the field resulted in that the movement was not necessary if the coil was dimensioned according to the right coil ground clearance class. If movement later would be of interest, it would be more beneficial to have it in the GA. This since the VA is more exposed to a harsher environment which leads to stricter demands of the mechanical structure. Also, the space is more limited in the vehicle compared to where the GA will be placed.

After discussions regarding integration with the OBC, it was realised that the electronic volume could be decreased. With an OBC integration, neither a rectifier nor a cooling system are needed in the VA. A reduction of the volume is of advantage since less modifications of vehicle components are needed which could result in lower cost.

From the matrix and evaluation, no concepts could be eliminated. This since a comparison with one concept was not considered to provide enough information for an elimination. However, some concepts were modified. The z movement was eliminated and the OBC integration added to all concepts. In the following, the concepts with an eliminated movement and/or added OBC integration will be called 2.0.

7.2.3.2 Later Evaluation of VA Geometry

To get enough information for taking a decision about which concept to further develop, a second concept screening matrix was executed. The matrix can be found in Table 7.3. The criteria *High charging efficiency* and *Low mechanical/electrical complexity* from the first matrix were excluded in the second matrix. This since these criteria were considered not being of relevance due to the modifications to make all concepts fixed in its position and integrated in the OBC. Instead, the criterion *Short cable distance* was added. This criterion compared the cable distance needed for all concepts to work. It was assumed to be of importance since a long cable distance could result in system losses and problems with EMC. The Fly concept was selected as the reference since this was one of the best scored concepts in the first concept screening matrix.

Table 7.3: Comparison of concepts in second concept screening matrix.

Concept screening matrix 2 - Geometry								
Criteria	Fly	Sandwich 2.0	Podium	Ladder 2.0	Pool 2.0	Snake 2.0	Swing 2.0	Robot
Few critical modfications of vehicle components	Reference	-	0	0	+	-	+	-
Multiple attachment possibilities		0	0	0	0	-	0	-
Many possibilities to protect VA		0	0	0	-	0	-	-
Ease to mount VA		0	0	0	-	-	-	-
Low number of parts		0	0	0	-	-	-	-
Short cable distance		0	0	0	-	-	-	-
Sum +	0	0	0	0	1	0	1	0
Sum 0	0	5	6	6	1	1	1	0
Sum -	0	-1	0	0	4	5	4	6
Net value	0	-1	0	0	-3	-5	-4	-6
Ranking	**1**	**2**	**1**	**1**	**3**	**5**	**4**	**6**

The second concept screening matrix clearly indicates that a single box concept is to prefer. All concepts that include ideas of splitting the electronic equipment into several boxes had lower scores in almost all categories compared to the Fly. However, a plus can be identified in the criterion *Few critical modifications of vehicle components* for the Swing 2.0 and the Pool 2.0. The Swing 2.0 concept is utilises a cavity in the platform in front of the sub frame for positioning the electronics. Even though available space is utilised, the position has drawbacks regarding cable distance. It was also found that the cavity had a purpose in form of airflow after the cooling system of the vehicle. A prevention of the airflow could lead to consequences for the overall performance of the vehicle. Therefore, the Swing 2.0 were eliminated. Also, the rest multiple boxes concepts were eliminated (the Pool 2.0, the Snake 2.0 and the Robot).

7.2.3.3 Final Evaluation of VA Geometry

The final evaluation of the VA geometry was made by discussions with employees at Volvo Cars together with analysis within the project group. Since all multiple box solutions had been eliminated, the final evaluation only analysed the geometry of the single box solutions. In order to make a fair assessment, more knowledge was needed about the sub frame. Critical parts and dimensions of the sub frame were discussed and evaluated with experts at Volvo Cars.

The evaluation with a responsible person of the sub frame at Volvo Cars resulted in that critical areas were found. For instance, there were some areas that included different features that could not be moved without large modifications of the entire platform. When these critical areas were found, analysis of each concept's geometry and the consequences of modifying the sub frame area to make them fit were executed.

Regarding the Sandwich 2.0, critical modifications of the sub frame were needed for the concept to be placed in its position. The modifications needed for the sub frame had large consequences of the overall platform design. The geometry of the concept was therefore not to prefer compared to the other concepts, which resulted in an elimination of the Sandwich 2.0 concept.

The Fly, with the electronics placed on both sides of the coil house, conflicted with two bolts in the sub frame. Also, an employee at the department of electronics at Volvo Cars highlighted an increased volume, weight and cost for this concept compared to the other concepts. This since extra wires and connections will be needed for the concept to function. Complementary, there was also concerns about splitting the electronic regarding the performance of the system. All these aspects resulted in an elimination of the Fly concept.

Finally, two concepts remained after the elimination, the Podium and the Ladder 2.0. Both concepts were developed to optimise the integration in the sub frame, fixed in their position and integrated with the OBC. A combination of the two concepts was considered to result in the optimal solution which is seen in Figure 7.12. This concept was called the PoLad and the shape of the electronics volume was inspired from both the concepts. The reason of combining the two remaining concepts was that it was realised that the volume of the electronics could decrease due to integration of the OBC. However, how large this volume reduction could be was at this stage not comprehended. Also, a combination was considered to be best to be able to adapt to the sub frame in the most convenient way. Further development of this combined chosen concept will be presented in the subsequent chapter.

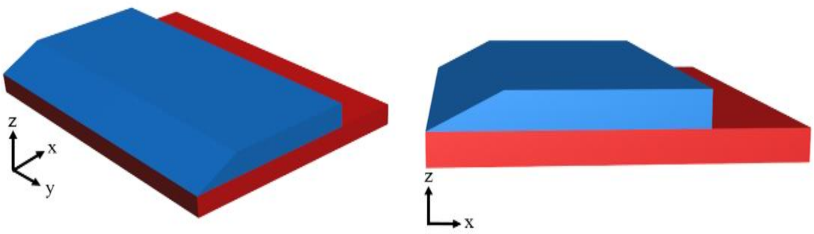


Figure 7.12: The final chosen concept, the PoLad.

7.3 Summary of Geometry Concept Development

In the first section of the chapter, inner constraints were determined. Analyses of different coil topologies were executed which resulted in a decision of using the Double D coil topology for further development. Specified dimensions of the coil house including coil, ferrites and coil housing were taken from the recommended practice SAE J2954, based on the Z and WPT class. The section followed by a determination of the electronic design space. This was determined to be 1.9 dm^3. Then, an investigation of already existing components in the platform was executed. This showed that the OBC could be utilised in the performance of the VA.

The concept generation of VA geometry resulted in different combinations and solutions of the geometry, movements and integration with the OBC. Single box and multiple box solutions were evaluated and compared by considering several criteria. Iterations of evaluations and redesign of concepts resulted in a combination of the Podium and the Ladder 2.0 concepts for further detailed design development. Both concepts were developed to optimise the integration in the sub frame, fixed in its position and integrated with the OBC. One of the reason for combining these concepts were their relatively low impact of the platform, meaning that fewer critical modifications would be necessary in the sub frame. In addition, their compact geometry could result in a reduced weight, volume, and cost. The final concept's name was the PoLad.

8 Detailed Design

In this chapter, it is described how the final concept was designed and modelled more in detail. The position of the VA in the platform as well as the geometry of the component were developed and determined in the previous concept development chapters, see Chapter 6 and Chapter 7. However, in the attempts to realise the final concept, the concept had to be designed more in detail to, for instance, fit in the platform and be possible to manufacture and assemble.

Throughout this chapter, environmental aspects, design for manufacturing and assembly, as well as costs and weight reductions were taken into consideration. In addition, ethical aspects were taken into account since no one should be affected negatively by using inductive charging. In this case the focus on EMC, and the attempts to avoid exposure of magnetic fields. In the case where it was not possible to fulfil all aspects equally, trade-offs between these aspects were made.

8.1 Components Modelling and Integration with OBC and Platform

This section explains the approach when modelling the different components of the VA in CAD. It also describes how the VA was integrated with the OBC but also in the platform. First, the strategy for executing the modelling and integrating is explained. Then, the results from each step is presented.

8.1.1 Strategy of Components Modelling and Integration with OBC and Platform

The modelling of the parts was performed in parallel. However, how the OBC could be utilised and integrated with the VA was done first to be able to estimate the volume reduction of the electronics needed in the VA. Then, the actual modelling of the components of the VA was initiated.

Further investigation of the OBC integration was made to fully understand the possibilities and consequences of the integration. First, analyses of the OBC were performed to understand its function. In this way, the wireless system was analysed. Thereafter, the both systems were compared and ideas for the integration were generated. The ideas were evaluated and discussed with an employee at the electrical department at Volvo Cars, which resulted in one concept to be selected. Based on the concept, an estimated volume reduction of the electronics equipment was executed. In addition, consequences of the redesign of the OBC were analysed and discussed.

When the volume reduction of the electronics was determined, the actual modelling of the VA was undertaken. The CAD tool used to model the components was Catia V5. The coil and ferrites were first modelled and then the other components were built around them. When building the model of the VA, there were several aspects to consider. To be able to end up in a design of the concept within the time frame, it was necessary to prioritise different aspects. Since the placement of the VA had been thoroughly investigated and determined, it was desirable to make as few critical modifications on the sub frame as possible. Another aspect being of high importance was the placement of the input and output of the VA, such as connectors and pigtails. Following in the prioritise order was the assembling of the VA. This means that the different components should be able to assemble. Manufacturing and the installation of the VA component into the platform are also aspects that should be taken into consideration. However, due to time constraints, these aspects were not put in main focus when designing the VA but were considered as far as possible.

The different components of the VA were modelled in several iterations. Ideas of how to build them were generated and then evaluated, both within the project group but also with different experts within certain fields. In the cases where a design of a component had to be selected, the determinations were supported by discussions and/or decision matrices. These discussions and matrices were based on the aspects and criteria put on the VA and based on the prioritisation of them.

8.1.2 Integration with On-Board Charger

The electrical circuit of the OBC is shown in Figure 8.1. The OBC utilises conductive charging which means that there is a physical connection between the coils. AC power with a frequency of 50 Hz is given to the system through the plug-in to the left in the figure. AC is converted to DC by the rectifier. Then, it is converted to AC again by the inverter, but now with a frequency of 85-100 kHz. The step is needed to increase the efficiency of the system. However, the AC is then transferred between the two coils. The transfer is needed due to galvanic isolation (Stock, 2016). After the transfer between the coils, the AC is converted to DC again and provided to the battery.

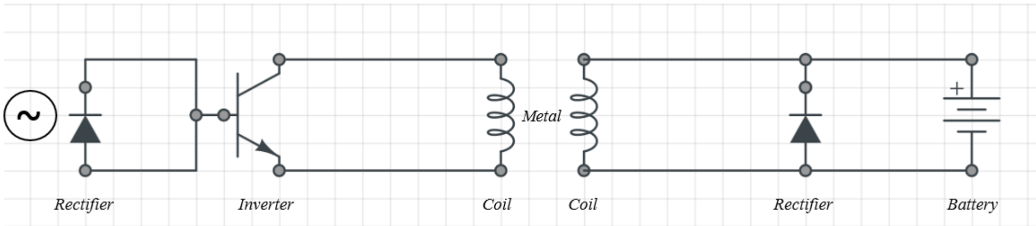


Figure 8.1: Illustration of the electrical system of the OBC.

According to Berntsson (2017), the wireless charging (WLC) system is similar to the plug-in charging system, see Figure 8.2. What differs the systems are mainly two capacitors, and a transfer of AC in the air. Again, AC is first converted to DC, to later be converted to AC again to increase the frequency. A capacitor is placed before and after the air transfer between the coils to compensate the phase shifts of current and voltage. The AC is converted to DC and then provided to the battery.

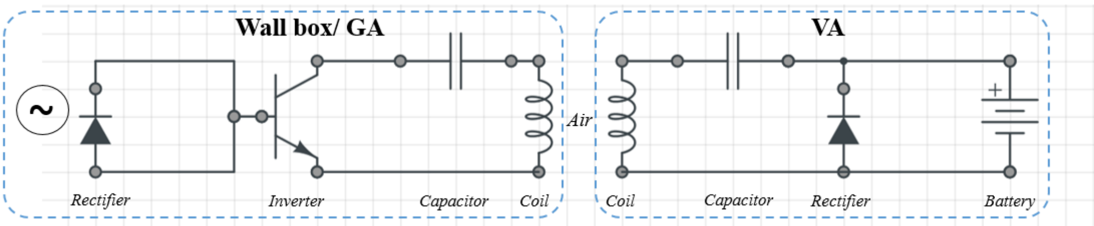


Figure 8.2: Illustration of the electrical system of the WLC.

The first idea of how to integrate the systems was to connect the VA with the OBC direct after the second capacitor, see Figure 8.3. The current would then be treated in the same way as for the plug-in. What to consider was the losses in both systems. The current will be transported a longer way, and the losses for the overall system will thereby increase. Since a frequency of 85 kHz is already achieved in the VA, this frequency would have to first decrease to the normal frequency of 50 Hz when entering the OBC. Then, it would again increase to 85 kHz when passing through the OBC which would lead to unnecessary efficiency losses.

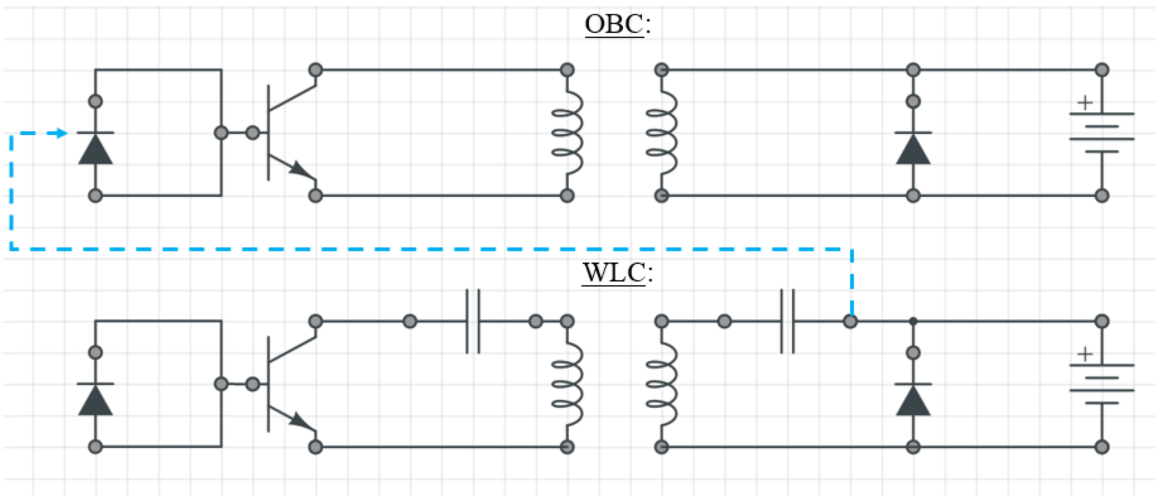


Figure 8.3: Illustration of the first idea of how to integrate VA with the OBC.

Compared to the first idea, the energy losses can be decreased if the components are connected as Figure 8.4 shows. Since the AC from VA already has a frequency of 85 kHz, there is no need to convert it again. Instead, the AC can directly be connected to the system after the second coil in the OBC. Thereby, the AC will be treated in the same way but in another component.

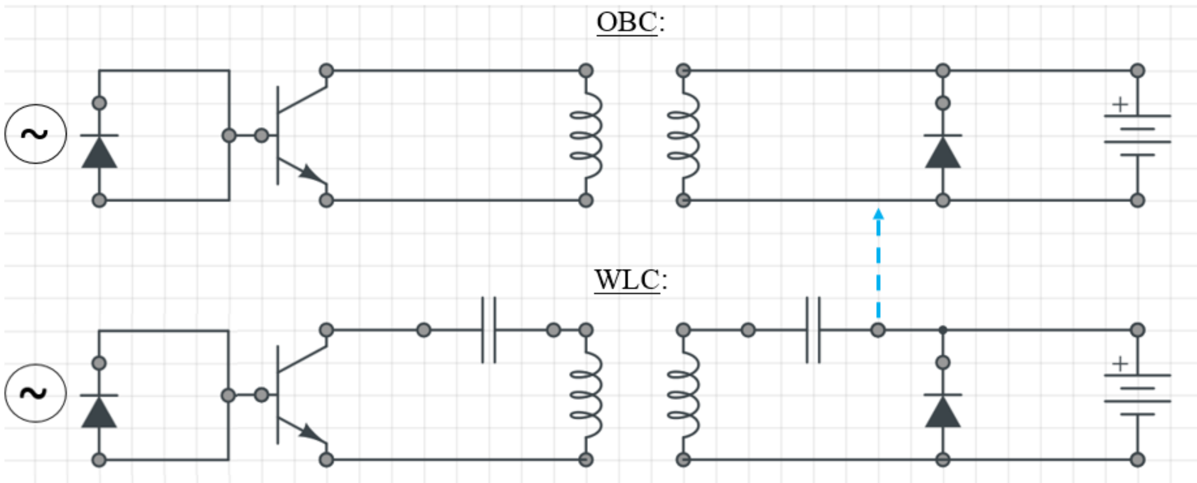


Figure 8.4: Illustration of the second idea of how to integrate VA with the OBC.

The both ideas were evaluated with an employee at the electrical department at Volvo Cars. Both ideas were considered to be feasible to realise, but idea number two thought to be even more appropriate due to lower efficiency losses in the system. The integration with the OBC would eliminate the need of the rectifier and cooling system from the VA, making the volume of the VA smaller. As explained in Section 7.1, the voltage and current sensors needed in the VA could be eliminated and instead utilise the OBC's already existing sensors. The employee estimated that the electronic volume of the VA could be decreased with approximately 40 % if the rectifier, cooling system and sensors in the OBC were utilised in the performance of the VA. The volume of the electronics was as mentioned estimated to 1.90 dm^3. With a reduction of 40 %, the volume of the electronics would instead be 1.14 dm^3.

However, the integration will result in redesign of the OBC. The OBC needs to be more robust and additional connector needs to be added, see Figure 8.5.

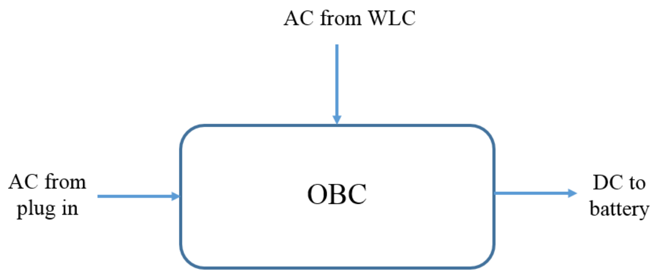


Figure 8.5: Representative illustration of inputs and outputs of the OBC.

Changes in the software of the OBC will also be needed. For instance, the risk of charging the battery with the WLC and plug-in systems at the same time needs to be eliminated. A redesign of the OBC could presumably result in a higher cost for the OBC. However, by excluding the rectifier and cooling system in the VA could result in lower costs for the VA. More about consequences and opportunities of this integration will be brought up in the discussions, see Chapter 10.

8.1.3 Coil and Ferrites Modelling

The coil and ferrites were dimensioned according to the SAE International recommended practice SAE J2954 for the classes WPT3 and Z2. As mentioned, the WPT3 corresponds to 11 kW charging and Z2 the coil ground clearance which is 140-210 mm. As established in Chapter 7, the coil will have the Double D design. The wire has three turns and a diameter of 4 mm. According to SAE J2954, the coil consists of two wires, one placed above the other. A litz wire is used which is a specialised wire used to carry AC. The wire consists of several individually insulated wires, which together are twisted. The result of the insulation and twisting is an equally distributed current with a low resistant. The ferrites are split into two parts and placed over the turned wires to direct the magnetic field. The coil together with the ferrites are visualised in Figure 8.6. The coil is represented in red colour while the ferrite is represented in grey.

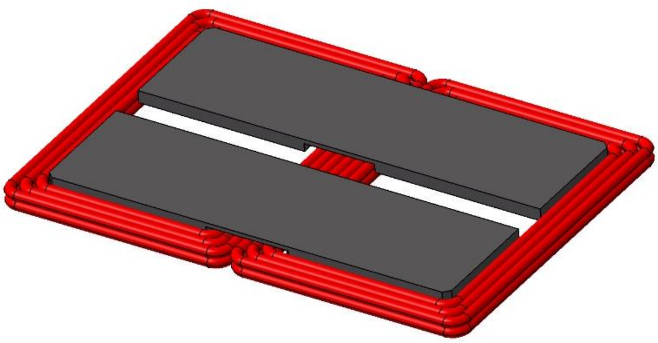


Figure 8.6: Visualisation of the coil and ferrites according to SAE J2954.

The geometry and design of the coil was fixed and not possible to redesign during the detailed design phase. However, the ferrites were up for refinements if needed. The reason for this was to achieve to most promising design of the VA as a complete component.

8.1.4 Electronic Housing Modelling

The electronics, except the connectors, were needed to be isolated from the coil area due to protection of magnetic field. The isolation was made by using metal, sealing and screws. As mentioned, the volume needed to fit all electronics necessary in the VA was estimated to 1 140 000 mm^3. The electronics were positioned over the coil housing, near the motor, in the final concept. Three ideas of how to protect the electronics were generated. The ideas included a box, a sink, and a cap. The ideas are presented in Figure 8.7. The electronics will be placed under or inside the blue components.

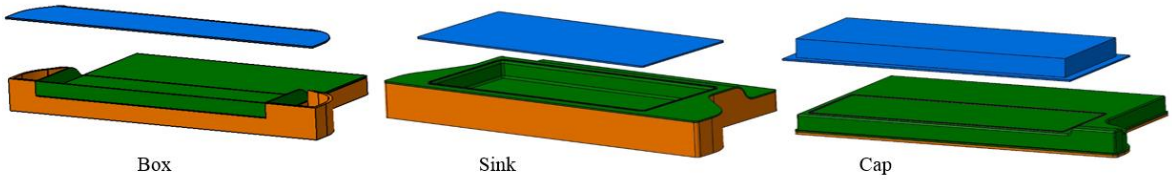


Figure 8.7: Different ideas of the electronic housing.

The first idea in Figure 8.7, the Box, had three walls and a floor integrated in one part. The electronics were isolated with a separated lid (represented in blue). The lid will function as a roof and a wall in the back, and was attached with screws. A sealing was placed between the components to avoid leakage in to the electronic components. The Sink differed in the function from the Box idea. In this idea, the lid only functioned as a roof. The walls and floor were integrated in the same part, while the lid was separated. However, the attachment was similar as the Box idea which included sealing and screws. The last idea, the Cap, was more or less like the sink but turned upside down. The Cap had walls in all directions together with a roof. The floor was separated in another part. Like the other ideas, screws and sealing were used to attach and isolate the electronics.

The ideas were compared in a concept screening matrix with the Box as reference. Suitable demands and wishes for the comparison and detailed level were picked from the requirement specification. The criteria picked were *Good isolation*, *Ease to manufacture*, *Ease to assemble* and *Low number of parts.* The matrix can be found in Table 8.1.

Table 8.1: Concept screening matrix of electronic housing.

Concept screening matrix - Electronic Housing			
Criteria	**Box**	**Sink**	**Cap**
Good isolation	Reference	+	+
Ease to manufacture		-	+
Ease to assemble		+	+
Low number of parts		0	0
Sum +	0	2	3
Sum 0	0	1	1
Sum -	0	1	0
Net value	0	1	3
Ranking	**3**	**2**	**1**

The concept screening matrix indicated the Cap as most promising. Overall, the concept could be easier to manufacture and assemble, and had a proper isolation. The number of parts were assumed to be equally for all concepts. The Cap idea was chosen to be further developed and integrated in the final design.

8.1.5 *Electrical Connectors*

Connectors are needed for the VA to being able to communicate with other vehicle components and to transport the produced current from the wireless transfer to the battery storage. Since it was decided to utilise the OBC, the conversion of AC to DC will not occur in the VA. Therefore, one connector needs to have a HV AC output so that the voltage can be transferred to the OBC where it then will be converted to DC and later transferred to the battery pack. The other connector needed was a LV signal for the communication which will be transferred to the 12 V battery in the vehicle. From the connectors, the voltages will be transferred through cords. The cords were not included in the project, only the connectors needed on the VA.

Several positions of the connectors were investigated to be able to find most suitable placements of them. During the investigation of position, an envelope which showed the movement of the nearby motor was used. The focus was to find a position where they did not conflict with critical components such as the motor. It was also desirable to make as few critical changes in the sub frame as possible. Different placements that were investigated can be found in Figure 8.8, where the red dot indicates HV connector and green dot LV connector. The VA is illustrated from below, where the dotted line indicates the volume and placement of the electronic housing.

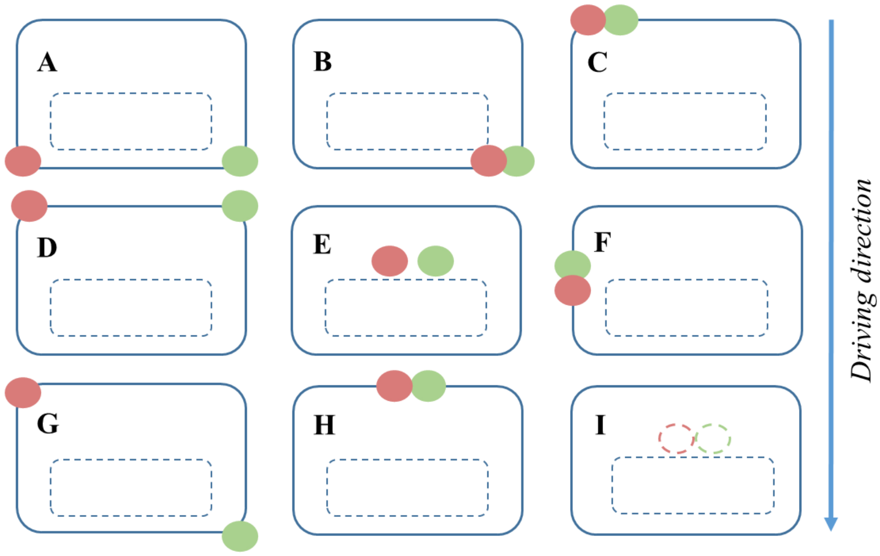


Figure 8.8: Different placements of the connectors.

Regarding the front of the VA, the analysis showed that it was only possible to place the connectors to the right, position B in Figure 8.8, due to the geometry and movement of the motor. Position A was therefore eliminated. The constraints regarding the modifications of the sub frame prevented all placements in the rear and middle part. Position C, D, F, G, H and I were therefore eliminated. However, the VA was placed at the ground clearance level which means at the lowest end of the car. Connectors pointing downwards, like E, were therefore impossible to realise. After the elimination, only position B remained.

There are different connectors that can be used. In this case, the more traditional connectors and pigtails were tested in the CAD model. The traditional connector uses a plug in enabling disconnection off the device, while a pigtail is fixed to the electronic device. The traditional connector is usually larger in volume. In this case, the traditional connectors were too large for the model. Therefore, pigtails were decided to be used for both the HV and LV.

8.1.6 Complete Concept Design and Platform Integration

When all the parts had been modelled, they were put together into one VA component. In Figure 8.9, the VA concept is illustrated. More pictures of the concept will be presented in this chapter but also in the subsequent chapter, final design.

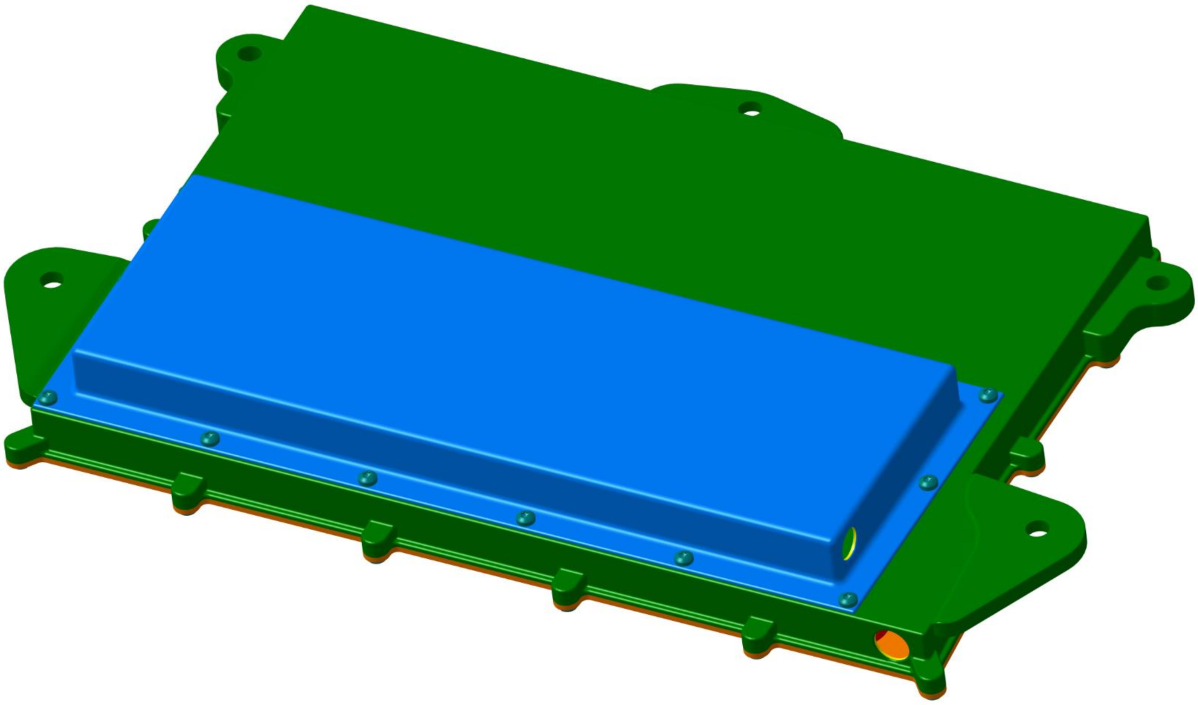


Figure 8.9: Final concept of VA.

The different parts of the VA have been illustrated in different colours. In the bottom, there is a coil cover where the coil is placed on. This cover is barely visible in the figure, however, it is represented in orange. Above the coil cover, the housing is placed. This is represented as the green part. The blue part is the electronic cover, and inside this cover, the electronics will be placed. Between these parts there are sealings which are shown later in the chapter. It can be seen that there are two larger holes, one in the bottom right of the housing and one in the electronic cover. Here, the input/output of the wires for the HV and LV will be located. As mentioned in the previous section, pigtails will be used for both the HV and LV. The HV cable which will transport the AC to the OBC will be mounted to the housing, while the LV cable for communicating and transporting current to the 12 V battery will be mounted to the electronic cover.

It can be seen that the electronic cover is placed in the front of the housing. The reason for this was to make as few critical modifications of the sub frame as possible. The geometry of the sub frame further back above the housing was assumed to be more critical. If touching this area, several modifications of the platform could have been necessary. The screw attachments which are the green small parts that are protruded from the housing, see Figure 8.9, are modelled to not clash with the sub frame. In this way, a smaller area of the sub frame could be cut out.

In Figure 8.9, five larger attachment ears can be seen. They have been modelled to fit in the selected position in the platform and are needed to be able to mount the VA to the sub frame. It was decided to have these integrated in the housing since it thereby more likely could manage more loads. In this way, the other parts of the VA was modelled to not be in need of manage these kinds of loads. Since the position of the VA is conflicting with the sub frame, the sub frame has to be modified. Such modifications have not been made in the project since the sub frame presumably will have to be reinforced to fulfil all its requirements. However, a cut out in the sub frame has been made to visualise where material of the sub frame has to be eliminated to fit the VA. In Figure 8.10, this cut out is shown and circled in red. The sub frame is blurred due to confidentiality.

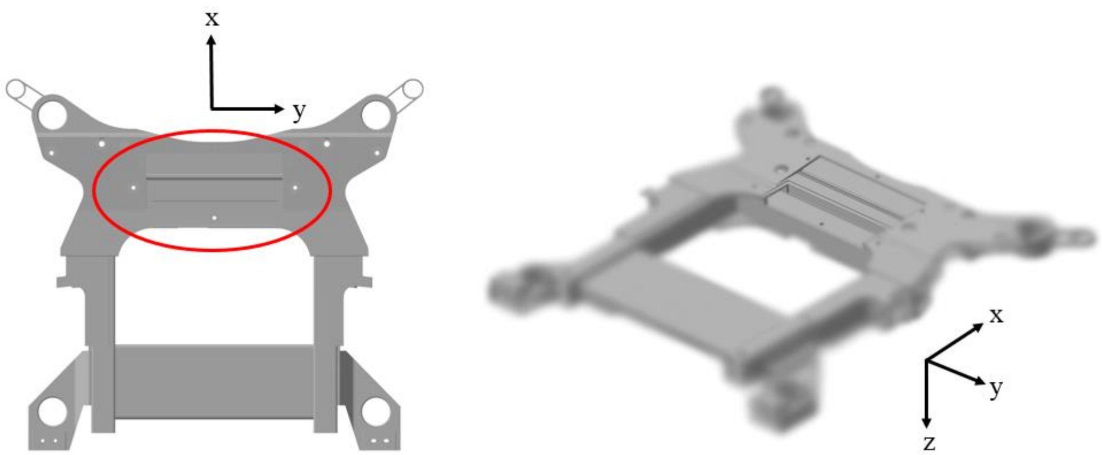


Figure 8.10: Models of the sub frame cut out. Partly blurred due to confidentiality.

In x and y direction, the cut out is 2 mm larger than the actual VA concept to easier put the VA in place. In reality, this offset could possibly have to be larger depending on which tolerances to use. This offset was only chosen to illustrate that some sort of space will be needed to be able to mount the VA in the sub frame. The holes needed in the sub frame to mount the VA to the sub frame have been made in the same plane and directions as the holes already present in the sub frame. This could ease the production of the sub frame. Figure 8.11 illustrates the VA mounted to the sub frame. No screws or bolts for the installation have been decided. The sub frame is blurred due to confidentiality.

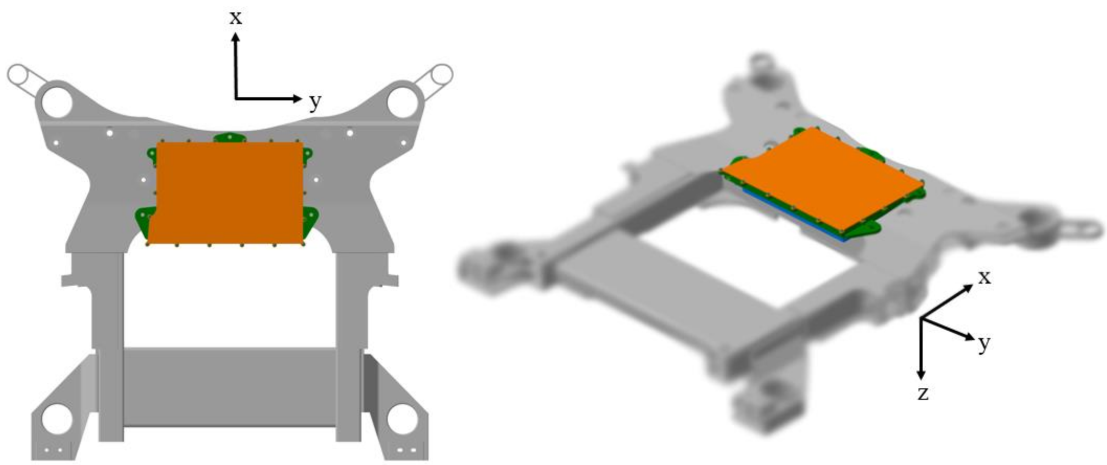


Figure 8.11: Visualisation of the VA positioned in place on the sub frame. Partly blurred due to confidentiality.

According to the recommended practice SAE J2954, an aluminium shield is needed that covers the bottom area of the vehicle around the VA. Since the GA is larger than the VA, there is a risk that magnetic fields also enter surrounding components when flowing to the VA. The ferrites in the VA will direct the magnetic field to the VA. However, the aluminium shield is also needed to prevent leakage of magnetic field into other components and reducing losses in the system, making the wireless transfer between the GA and VA as efficient as possible. When examining the bottom of the vehicle, it was discovered that an undershield already exists below the vehicle. Therefore, it was concluded that this undershield could be utilised for the aluminium shield needed. In Figure 8.12, a concept of how this shield could look like is visualised in blue. A cut out to fit the VA in the shield has been made. Also, material has been added to the undershield behind the VA to cover as much as possible around the VA. This added part is circled in red in the figure. It can be seen that this part is slightly elevated. The reason for this is to leave this space for the battery component already present in that position. The aluminium shield is blurred due to confidentiality.

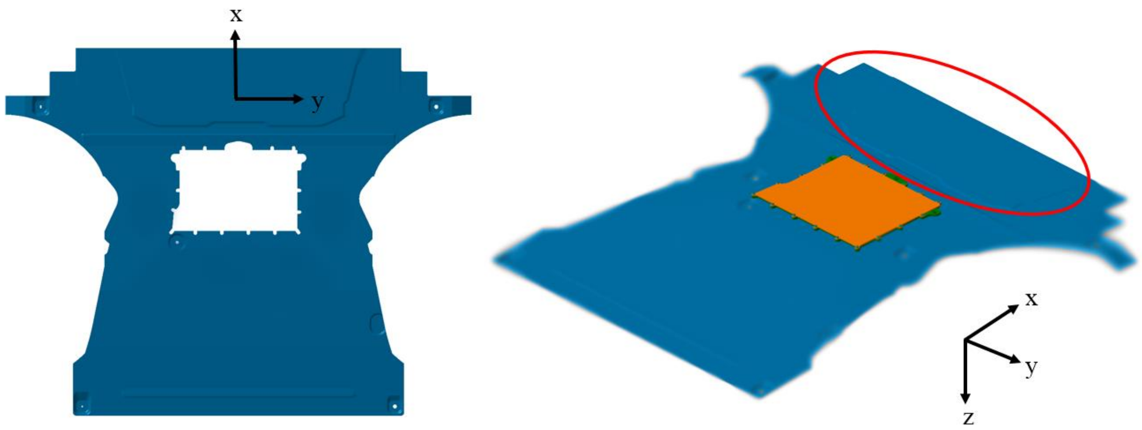


Figure 8.12: Aluminium shield integrated in undershield, to left without VA and to right, the VA positioned in place. Partly blurred due to confidentiality.

The existing undershield in the platform is produced in plastic, but the shield needed for magnetic field exposure protection should be in aluminium. Therefore, several suggestions of how to integrate the aluminium shield with the undershield were stated. The first idea is that the material of the entire undershield could be changed from plastic to aluminium. In this way, only one material is needed. Why it has been decided that this shield should be in plastic could have several reasons. One drawback of changing to aluminium is that the weight of the shield will possibly increase. The other idea was that one layer of the shield could be in aluminium and one in plastic. The plastic layer could be at the bottom, nearest the road, while the aluminium layer is placed above the plastic. In this way, if the shield gets scratched, there is a lower risk that the aluminium layer will be affected. This idea will also, however, increase the weight of the component, but presumably not as much as the first idea. The third idea was that an aluminium spray coating could be used on the plastic undershield. If this kind of spray coating will be sufficient to prevent magnetic field leakage has to be examined. In addition, it has to be tested if this aluminium coating will stick to the plastic. Since the main focus in the project was on the VA, no decision of what idea for the aluminium shield has been selected, only that it could be integrated by the existing undershield.

8.2 Material and Manufacturing Selection

Materials and manufacturing processes were selected based on each part's properties. First, a screening of existing components was performed to gain an understanding of common used classes of material. This, together with a study of specific properties for each component resulted in a selection of material class for each part. A more detailed investigation was thereafter performed with the software CES EduPack. Limitations were set in the software regarding temperature, price, density as well as mechanical properties to screen materials. Suitable materials were thereafter plotted to find advantages and disadvantages of each. Then, a suitable material was selected for each component. The manufacturing process for each part was chosen based on the material, part size, shape, required tolerances together with predicted batch size. The compatibility matrices according to Ashby (2011) were used as guidelines.

Common criteria as well as chosen material class for each part in the concept are listed below, see Table 8.2. By studying the specific properties and criteria for each part, and according to the recommended practice SAE J2954, it could be concluded that the coil cover should be produced in plastic. This due to the magnetic field generated by the GA which needs to be received by the coil without any disturbance to increase the efficiency of the system. The housing of the VA should be produced in metal in order to reduce exposure of the magnetic field and protect the electronics. However, the electronic cover had no constraints regarding exposure of magnetic field since it is placed above the housing. Therefore, the cover could be made in plastic. The material of the sealings needs to have a high degree of resilience. In this case, an elastomer could be an appropriate material choice for the sealings. In Figure 8.13, a model of the VA is shown. The coil cover is represented in orange, while the housing and electronic cover is represented in green and blue respectively.

Table 8.2: Criteria for the VA and material classes chosen for each part.

Criteria for VA	**Demand (D)/ Wish (W)**
Operational temperature: -40°C to 85°C	D
Water resistant	D
Non-magnetic	D
Life time > 15 years	D
Impact resistant	W
Low density	W
Low cost	W
Recyclable	W

Parts	**Material class for each part**
Coil cover	Plastic
Housing	Metal
Electronic cover	Plastic
Sealing	Elastomer

Figure 8.13: 3D modelled VA concept; coil cover (orange), housing (green), electronic cover (blue).

In the following, more details about which plastic and metal that would be suitable for each part are explained. Based on the material and the geometry of each component, different manufacturing processes were analysed and selected. No further investigation of which elastomer to use for the sealings was made due to the detailed level of the concept.

8.2.1 Plastic

When deciding which plastic that should be used for the coil and electronic covers, constraints on Young's modulus, yield strength, fracture toughness, temperature, magnetic properties and resistance against water were set in the CES EduPack software. The both parts were considered to be made in the same plastic since they needed to fulfil similar constraints. The first plot displayed the relation between Young's modulus and density which showed three promising candidates; polymethylpentene (PMP), propylene (PP) and polyethylene (PE). The plot can be found in Appendix G1. The other plot, see Figure 8.14, showed the relation between price and density for the plastics. Low density and price were desired to accomplish a light and cheap component as possible.

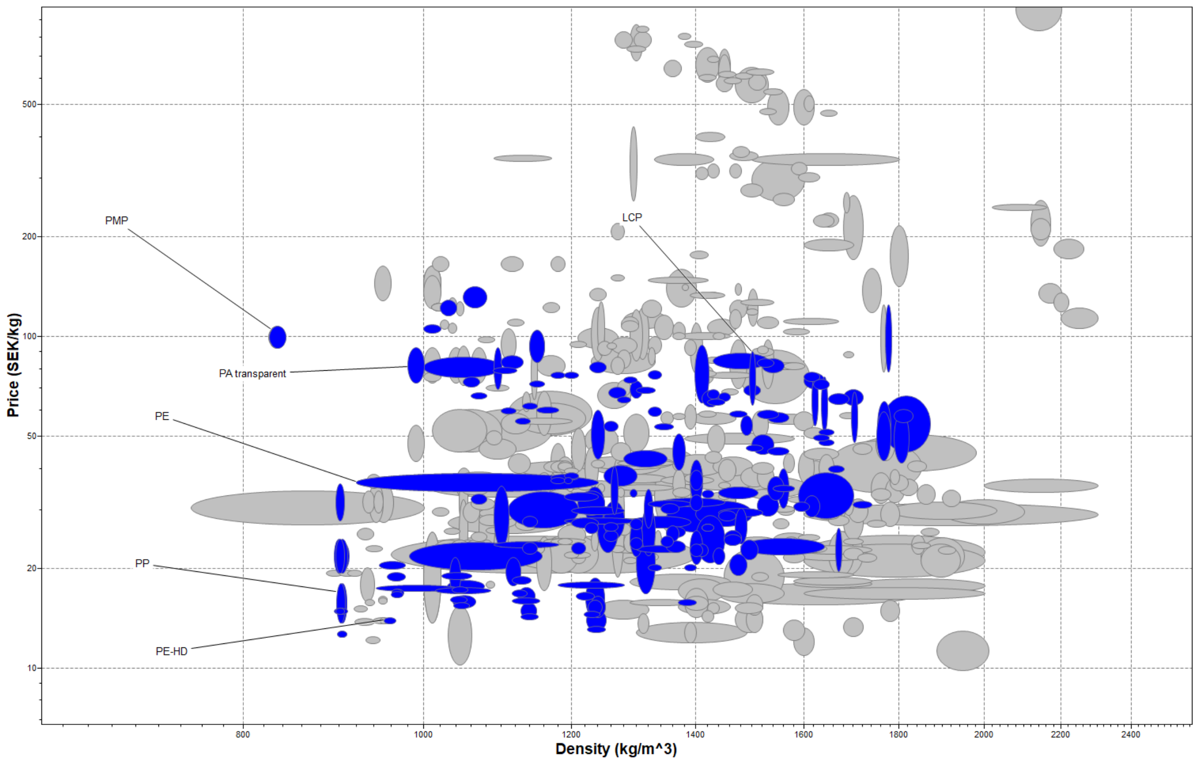


Figure 8.14: Plot showing the relation between price and density of the plastic parts.

The plastics which both had a low density and price were PE and PP. Therefore, PMP was eliminated. The properties of the materials left were further investigated. Compared to PP, PE had better impact resistance in a wide temperature range, higher fracture toughness and Young´s modulus. In temperatures lower than 20 °C, PP was brittle (Klason & Kubát, 2005). However, PE was found to be common used in the automotive industry. By taking these aspects into consideration, PE was chosen to be used for the covers for the coil as well as the electronics.

The manufacturing process was chosen based on the material, part size, shape, required tolerances together with predicted batch size. According to the material-process compatibility matrix (Ashby, 2011), the processes available for thermoplastics were different kinds of moulding, thermos-forming, polymer casting, and resin-transfer moulding. Next aspect to consider was the process-shape compatibility. Due to the geometry of the component, blow moulding, rotational moulding, thermo-forming, and polymer casting were eliminated. However, when further analyses of the mass and thickness of the component were made, the resin-transfer moulding and compression moulding were eliminated. Left was the injection moulding, which after further analysis felt reasonable due to tolerances and batch size according to the process tolerance chart and economic batch size chart (Ashby, 2011).

8.2.2 Metal

Constraints on price, density, temperature, mechanical properties, durability and recyclability were set in the CES EduPack software. The first plot displayed the relation between Young's modulus and density which resulted in three promising candidates; aluminium, brass, bronze, and stainless steel. The plot can be found in Appendix G2. The other plot, see Figure 8.15, showed the relation between price and density for the metals.

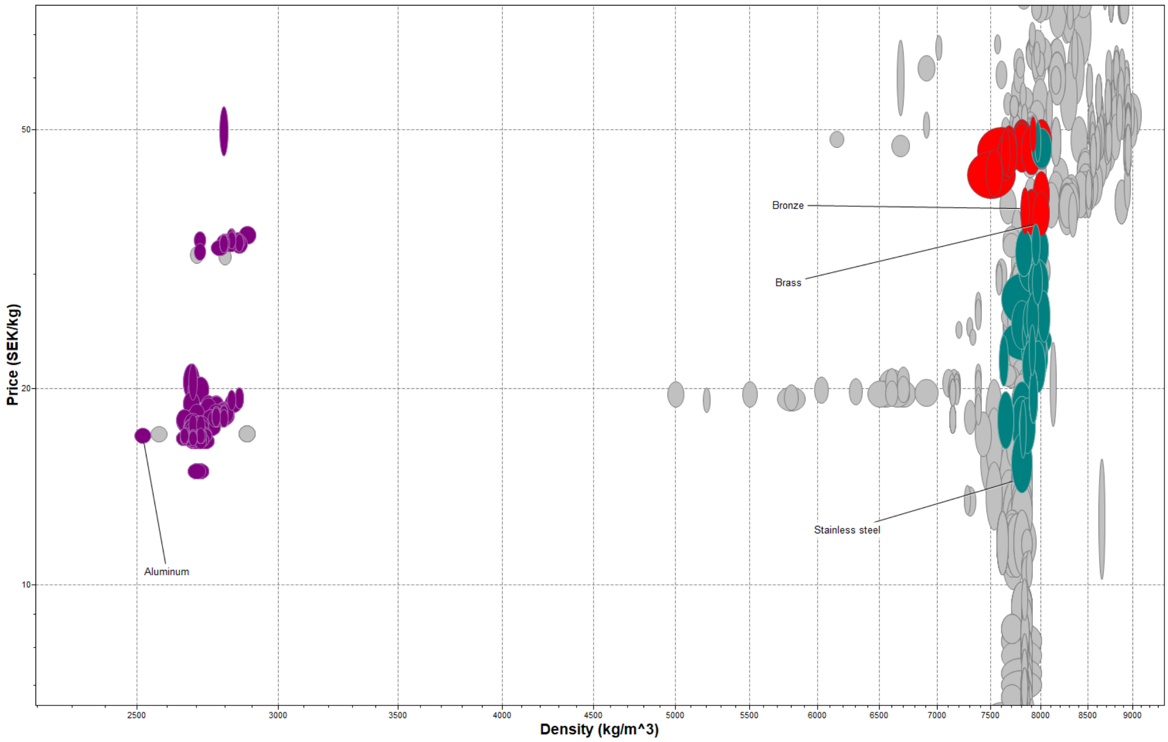


Figure 8.15: Plot showing the relation between price and density of the metal part.

The plot indicated a large difference in density between aluminium (purple) and the rest of the metals. Depending on composition, the aluminium could differ in price between 17-55 SEK/kg. Stainless steel followed the same pattern, while bronze and brass had higher prices. Therefore, bronze and brass were eliminated. Aluminium had approximately one third of the mass compared to steel. A low weight was beneficial since it, for instance, means lower energy consumption in transportation and less wear of the roads. A low density could also be of advantage during assembly. Since both aluminium and stainless steel met the mechanical constraints, but aluminium had advantages in density and price, aluminium was chosen to be used for the housing.

Similar to the plastic parts, the manufacturing process was chosen based on the material, parts size, shape, required tolerances and predicted batch size. According to the material-process compatibility matrix (Ashby, 2011), the processes available for metals are different kinds of castings, forging, extrusion, sheet forming, powder methods, and electro-machining. Next aspect to consider was the process-shape compatibility. The housing made of aluminium has three-dimensional characteristics and needs to be solid due to its mechanical properties. These criteria eliminated the extrusion and sheet processes. This since the extrusion only creates axisymmetric shapes, and the sheet process flat or dished shapes. However, next criteria to consider were the mass and section thickness since there are limits of the size that the processes can manage. The analysis showed that powder methods and electro-machining were not appropriate due to the weight of the component. Considering a 2 mm thickness, forging was excluded. The only process that remained after the elimination was casting. Further analyses of casting showed that the process had an economic batch size, small tolerance could be reached and that similar components in the industry use the process. Therefore, the housing was decided to be casted in aluminium.

8.3 Design for Assembly

When designing the components of the VA, design for assembly had to be taken into consideration. This since the assembly process should be as convenient as possible in order to decrease the total cost. First, the order of the process was decided. Then, each step was examined to get an understanding of the process. This resulted in that features were redesigned. The holes on the coil and electronic covers from where the screws will be inserted were made slightly larger than the holes in the screw attachments in the housing where the screws are tightened. The reason for this was to ease the assembly process since only the screw holes in the housing were threaded. For the electronic cover, the position of the screw holes were changed to prevent that the cover could be mounted in the wrong direction. In addition, the geometry of the ferrites has been adapted for the placement of the coil.

The coil, ferrites and housing are in focus in the first and second step of the assembly process. Protruding cylinders in the housing are designed to place the ferrites in their correct position, which is done in the first step. Thereafter, the coil is placed above the ferrites in the second step. As mentioned, the ferrites are dimensioned to guide the assembly process of the coil. These steps of the assembly process together with a more detailed view of a protruding cylinder are seen in Figure 8.16.

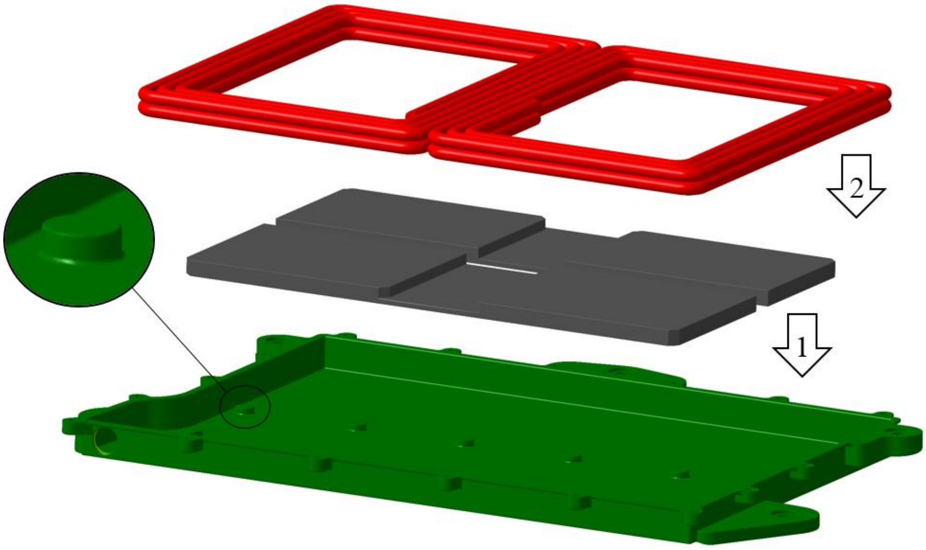


Figure 8.16: Visualisation of the first and second steps of the assembly process.

In the third step of the process, the coil cover is placed on the housing. The sealing and the geometry's dissymmetry prevents the coil cover to be mounted in wrong direction. The sealing which is placed between the coil cover and housing is already placed in the sealing track in the cover. The sealing is placed inside the screws to avoid leakage from the screw holes entering the VA. In the fourth step, 18 screws are used to fasten the cover to the housing. The distance between the screws is approximate and based on the distance between the screws on similar components in the platform. As mentioned, the holes for the screws in the coil cover are modelled slightly larger than the holes in the housing. It was chosen to use screws for assembling the parts due to maintenance and disassembly. In the end of the VA's life time, the different materials should be able to separate from each other. By using screws instead of, for instance, glue, the parts can be separated conveniently. This is of advantage when having environmental aspects in mind. The assembly process and more detailed views of the screw attachments and sealing are visualised in Figure 8.17. The sealing is represented in purple colour.

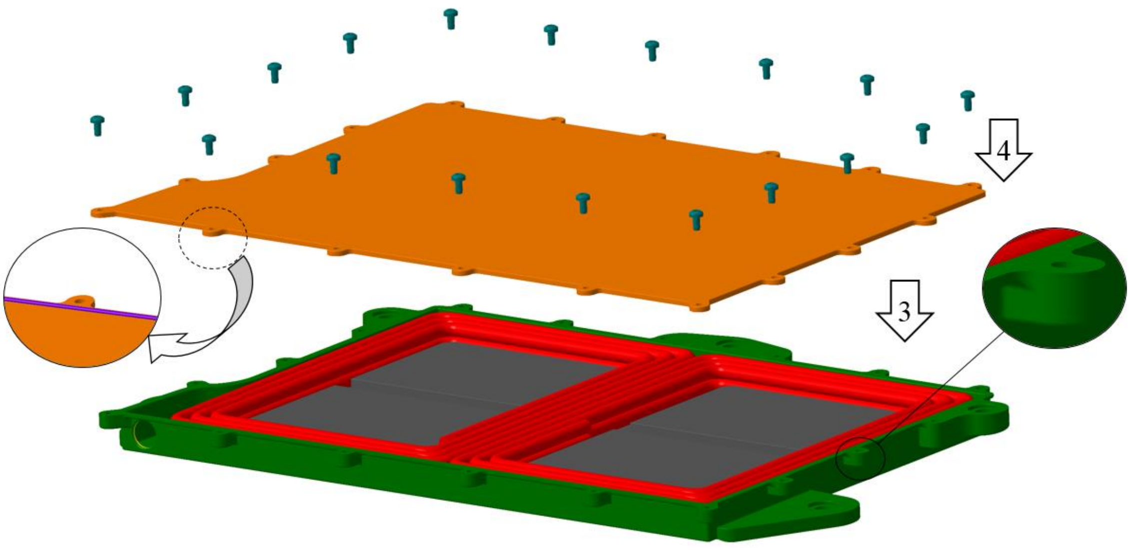


Figure 8.17: Visualisation of the third and fourth steps of the assembly process.

In the fifth step, the electronic cover is positioned on the housing. The attachments of the screws have been positioned in a way to prevent the cover to be mounted in wrong direction. Inside the cover, the electronics needed for the VA to work are already put in place. Also, the sealing which will be placed between the housing and electronic cover is already placed in the sealing track in the cover. The electronic cover is thereafter in the final, sixth, step fastened in the housing with 14 screws. The screw holes in the electronic cover are for the same reason as the other holes in the coil cover made slightly larger than the holes in the housing. The process together with a detailed view of the screw holes and sealing are visualised in Figure 8.18. The sealing is represented in pink colour.

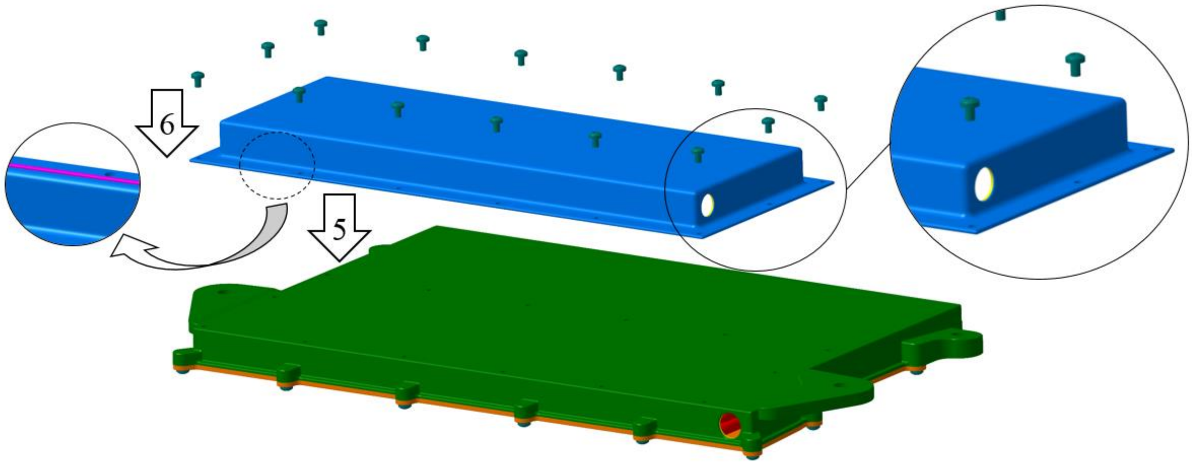


Figure 8.18: Visualisation of the final steps of the assembly process.

8.4 Manufacturing Cost Estimation

The manufacturing cost for each part was calculated with the software CES EduPack. The software took the mass, length, batch size, manufacturing process, part complexity, load factor, overhead rate and capital write off time into consideration. For all parts, the batch size was set to 1 000 units and the load factor to 67 %, meaning the production will run for 16 hours/day. The parts were assumed to be produced in Europe which resulted in an overhead rate of 1 130 SEK/hour. The overhead rate included cost of running the facility, meaning that the local labour rates and energy costs were included. The capital write off time was assumed to be five years. For each part, the mass, length, material and manufacturing process were selected individually. Each part’s characteristics together with its calculated manufacturing cost are listed in Table 8.3. The cost listed was the mean value of the manufacturing cost range.

Table 8.3: Summary of each part's characteristics and its calculated manufacturing cost.

Part	Mass [kg]	Length [mm]	Material	Manufacturing process	Cost [SEK]
Coil cover	0.297	415	Polyethylene	Injection moulding	62
Housing	0.989	415	Aluminium	Casting	199
Electronic cover	0.136	375	Polyethylene	Injection moulding	51
Ferrites	4.471	330	Iron	Casting	186
Coil	1.010	380	Litz wire (Copper)	Wire drawing	50
Sealing 1	0.005	406	Elastomer	Extrusion	5
Sealing 2	0.003	357	Elastomer	Extrusion	3
Screws – M4 (18 units)	0.004	8	Stainless steel	Thread rolling	9
Screws – M4 (14 units)	0.003	6	Stainless steel	Thread rolling	7
Total manufacturing cost [SEK]					**572**

The total manufacturing cost was estimated to 572 SEK. Since mean values of the manufacturing cost ranges for each part were used, the total cost for the VA was assumed to differ with 10 %. This means a manufacturing cost within the range of 515-630 SEK. The cost was approximate and based on several assumptions. However, it can be seen that the housing and the ferrites have the highest manufacturing cost. The reason for the high manufacturing cost could be the component design, material or selected manufacturing process. The housing was selected to be produced in aluminium due to the low cost of the material. The component was designed with a goal of decreasing the volume, and thereby the mass and length. Left is the manufacturing process which probably could be even more optimised for the component which could lower the cost. The material for the ferrites was selected based on the recommended practice SAE J2954. However, the design of the ferrites may not be optimal and both the length and mass could probably be reduced. Complementary, the manufacturing process could probably be changed to decrease the total cost of the component.

Regarding the total cost for the VA, there are more aspects that need to be taken into consideration. For instance, costs for development, assembly, distribution, administration, and marketing need to be added. Due to the concept level of the VA, these aspects were not taken into account in the project. However, the manufacturing and assembly process were taken into consideration when developing the VA. Changes to the design have been made during the project to ease the manufacturing and assembly process, and thereby decrease the total cost of the component. A licence must to be bought for using the Double D coil design which needs to be added to the total cost of the component. Also, the OBC needs to be redesigned to handle two charging processes, and modifications of the sub frame and undershield are needed. Costs for these changes also need to be considered when calculating the final cost of the implementation. However, the placement and design were carefully investigated and selected based on criteria such as *low modifications of vehicle components*. Therefore, the cost for these modifications were considered to be minimised.

9 Final Design

The detailed design resulted in a final design of the vehicle assembly, changes in the existing sub frame together with an aluminium shield. An exploded view of all components is illustrated in Figure 9.1. It can be seen that the aluminium shied has a cut out for the VA. The sub frame and aluminium shield is partly blurred due to confidentiality.

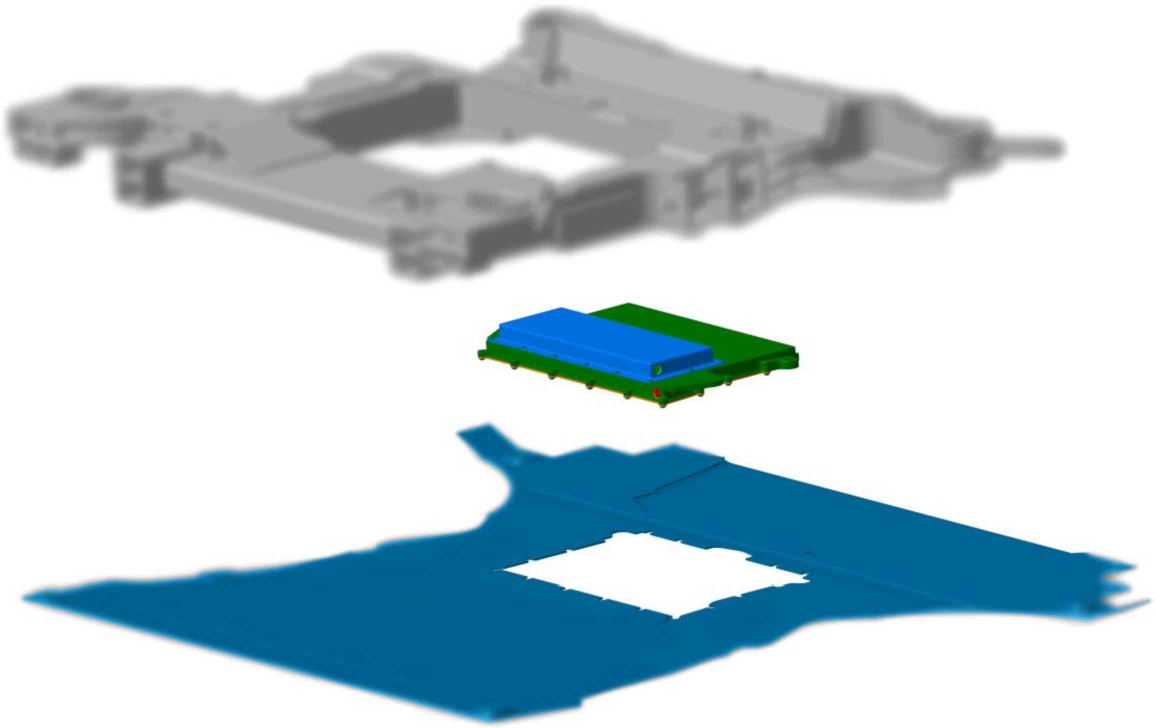


Figure 9.1: Exploded view of sub frame, vehicle assembly and aluminium shield. Partly blurred due to confidentiality.

In this chapter, the design of each part is explained and visualised. This follows by an evaluation of the fulfilment of the requirement specification.

9.1 Vehicle Assembly

The VA consists of eight parts plus 32 screws. All parts and screws are visualised in an exploded view in Figure 9.2 with an item letter connected to each part. The coil, D, is of the Double D design and is dimensioned according to the recommended practice SAE J2954. The coil is positioned in the housing. Over the coil, two ferrites, E, are positioned. A coil cover, B, made of plastic is placed under the ferrites and housing. The coil cover and housing are sealed by a sealing and 18 screws. The housing has a hole for the HV pigtail connection, and attachment ears to fasten the whole component in the platform.

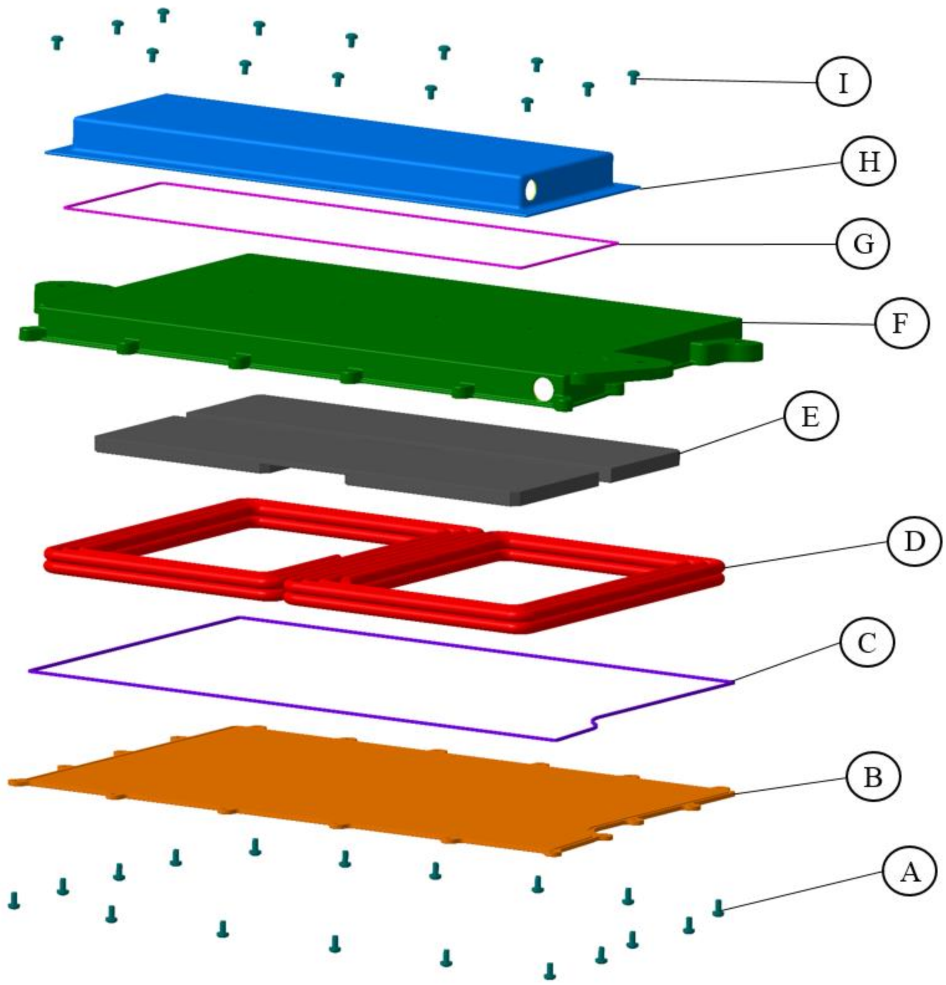


Figure 9.2: Exploded view of the developed VA.

On top of the housing, the electronics needed are placed. The electronics are covered by an electronic cover, H. The housing and cover are sealed by a sealing, G, and 14 screws. All parts, their quantity, material and weight are listed in the bill of materials in Table 9.1.

Table 9.1: Bill of materials for the vehicle assembly.

Item	Specification	Quantity	Material	Mass [kg]
A	Screws - M4, length 8 mm	18	Stainless steel	0.004
B	Coil cover	1	Polyethylene	0.297
C	Sealing 1	1	Elastomer	0.005
D	Ferrites	2	Iron	4.471
E	Coil	1	Litz wire (copper)	1.010
F	Housing	1	Aluminium	0.989
G	Sealing 2	1	Elastomer	0.003
H	Electronic cover	1	Polyethylene	0.136
I	Screws - M4, length 6 mm	14	Stainless steel	0.003

The total weight of the component excluding the electronics was approximately 7 kg. The assembled VA together with its outer dimensions are visualised in Figure 9.3. In the figure, it can be seen that the maximum height of the component is 50 mm. The length, y direction, and width, x direction, are mainly dimensioned according to the recommended practice SAE J2954. The length is slightly longer in the front of the VA due to the placement of the HV connector.

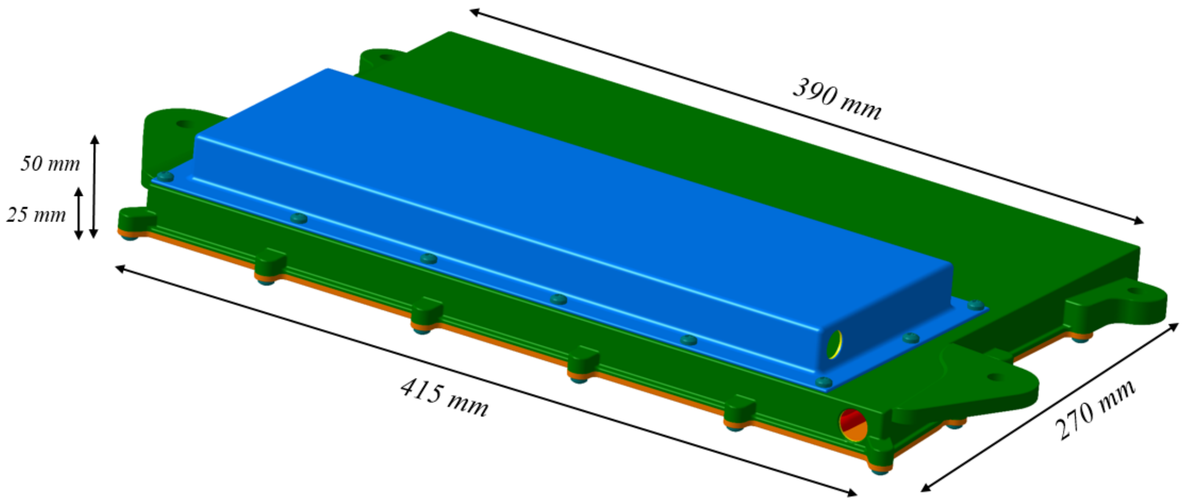


Figure 9.3: Outer dimensions of VA.

9.2 Sub Frame and Aluminium Shield

The sub frame was modified to fit the VA. The modified sub frame is visualised in Figure 9.4. The sub frame has a cut out in order to position the VA at ground clearance. The holes to attach the VA are put in the same direction as the already existing holes in the sub frame. The sub frame is blurred in the figure due to confidentiality.

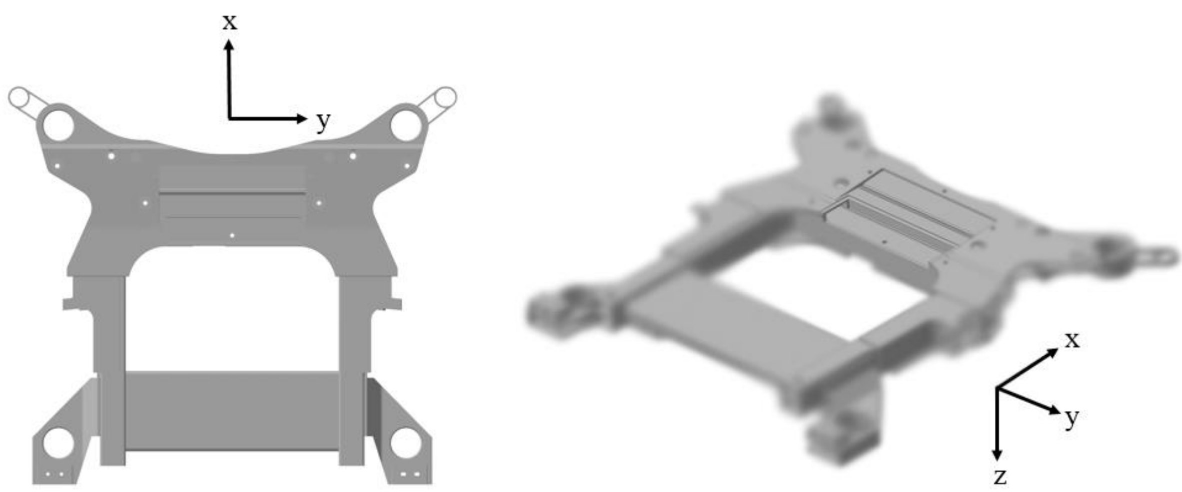


Figure 9.4: Modified sub frame. Partly blurred due to confidentiality.

The aluminium shield was made by modifying the undershield in the platform. The shield has a cut out for the VA. Extra material is added at the rear part of the shield to protect the battery component from magnetic field exposure. The aluminium shield can be found in Figure 9.5. The aluminium shield is blurred due to confidentiality.

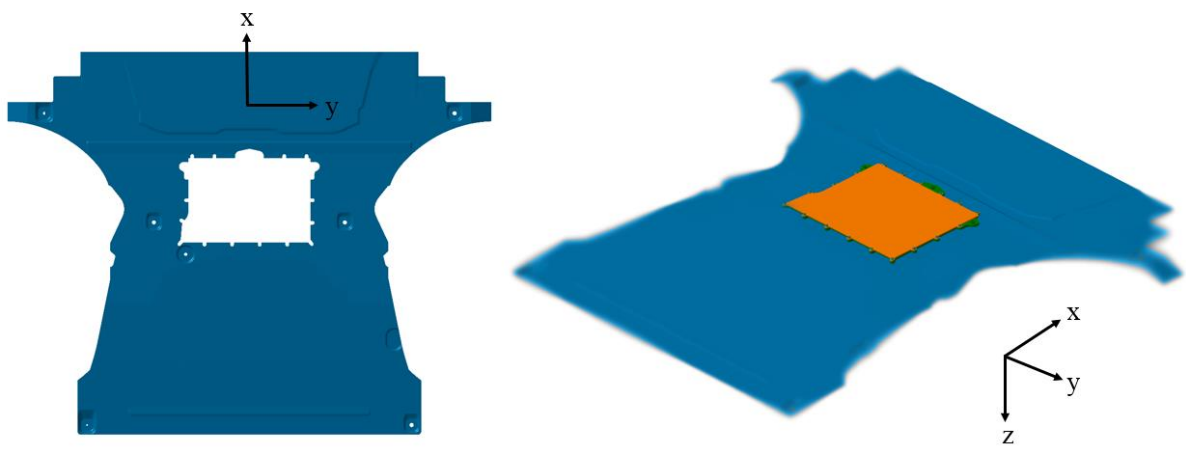


Figure 9.5: Visualisation of the protection shield. Partly blurred due to confidentiality.

9.3 Fulfilment of Requirement Specification

During the development of the final concept, the requirement specification has continuously been reviewed to evaluate to what extent the emerging solution fulfils the demands and wishes. The requirement specification was established for a future development of the VA. Due to the early stages of the development, only a geometrical concept of the VA has been developed. However, electronics needed for the VA to work are not present in the concept. Therefore, for some criteria, it has been difficult to verify their fulfilment. In the following, all criteria are listed and explained to what degree they have been fulfilled. *Green* indicates that the criterion has been taken into consideration carefully during the project and has been fulfilled for this geometrical concept. *Yellow* indicates that the criterion has been taken into consideration but has not been verified. *Red* however, indicates that the criterion has not been taken into consideration or been able to verify due to the detail level of the concept. The criteria are divided into the seven different areas based on the requirement specification. The requirement specification can be found in Appendix B1. The performance criteria are listed in Table 9.2.

Table 9.2: Degree of fulfilment for the performance criteria.

Criteria	Target value/specification	D/W	Degree of fulfilment
1.1 Power input	11 kW	D	Green
1.2 Power efficiency	> 90 %	D	Yellow
1.3 Operational temperature	-40°C to 85°C	D	Green
1.4 Life time	> 15 years	D	Red
1.5 Life time	> 5 475 cycles	D	Red
1.6 Operating frequency	85 kHz	D	Green
1.7 Strength	Manage its own load	D	Yellow
1.8 Collision safety	No open electrical circuit	D	Red
1.9 Collision safety	Not affecting the deformation negatively	D	Yellow

The criteria *1.1 Power input* and *1.6 Operating frequency* have been taken into consideration during the development since the component has been dimensioned with these constraints in mind, and followed the recommended practice SAE J2954. *1.2 Power efficiency* has also been taken into consideration, but has not been able to verify since the efficiency depends on the entire wireless charging system. Regarding *1.3 Operational temperature*, materials that will withstand the temperature range have been selected for the different parts of the VA. Therefore, these criterion has been fulfilled. The two criteria regarding life time are indicated with red. This since they have not been prioritised and more testing and refinement have to be accomplished in the further development. When designing the VA, considerations of making a robust component have been taken. For instance, the VA has been designed so that the housing component in aluminium will take most of the load. However, the degree of fulfilment for the criterion *1.7 Strength* is coloured in yellow since no strength calculations or tests have been undertaken. The criterion *1.8 Collision safety* has not been regarded due to the lack of the electronics in the concept. *1.9 Collision safety* has been taken into consideration since the placement of the VA has partly been selected due to this constraint. However, the position and geometry of the concept have resulted in that necessary modifications on the sub frame have to be made. The sub frame will be needed to be reinforced to maintain its expected performance in, for instance, collisions.

In Table 9.3, the functional criteria together with their degree of fulfilment are listed. Most of these criteria are fulfilled, but three criteria have not been able to verify. *2.1 Electronic interference* has not been prioritised. It is therefore difficult to verify that the VA will be disturbed by electronics in the surrounding environment. Both *2.2 Electromagnetic compatibility* and *2.3 Exposure of magnetic field* have been taken into consideration. The aluminium plate integrated in the undershield will prevent that the VA disturb surrounding components in the vehicle. The selected position of the VA was partly decided to affect the driver and passengers as little as possible. However, tests have to been undertaken to ensure that these two criteria are fulfilled.

Table 9.3: Degree of fulfilment for the functional criteria.

Criteria	**Target value/specification**	**D/W**	**Degree of fulfilment**
2.1 Electronic interference	Not being disturbed by electronics	D	Red
2.2 Electromagnetic compatibility	Not disturb electronics surrounding	D	Yellow
2.3 Exposure of magnetic field	Not affect living beings	D	Yellow
2.4 Leakage proof	No moisture inside component	D	Green
2.5 Driving performance	Not affected negatively	D	Green
2.6 Customer experience	Not affected negatively	D	Green
2.7 Compatible with critical vehicle components	VA not affecting negatively	D	Green
2.8 Manage misalignments	High efficiency when misaligned	W5	Green
2.9 Impact resistant	Withstand bumps and scratches	D	Green

Regarding *2.4 Leakage proof*, the VA consists of sealings between the different parts which will prevent moisture or liquid to enter the component. Since the VA has been designed with this criterion in mind, it is seemed to be fulfilled. For this kind of component, it is of high relevance that neither the driving performance nor the customer experience are affected negatively. This since the VA should attract customers and that the car should behave as expected. These are seemed to be fulfilled since the position of the VA has been decided based on these criteria. For instance, it will be convenient to manoeuvre the vehicle over the GA since it is placed in the front. Also, the customer will not need to plug in a cord, since the charging of the battery will start automatically if parked over the GA. The VA must be compatible with critical vehicle components, meaning the VA must not affecting these components negatively. By placing the VA at the decided position, this criterion was fulfilled. The criterion *2.8 Manage misalignments* ensured that an efficient wireless power transfer is achieved even when the VA is misaligned to the GA to some extent. Based on this criteria, the Double D coil topology was selected instead of the Circular coil topology. The last functional criteria was *2.9 Impact resistant* which states that the VA should withstand bumps and scratches. The material of the coil cover, which is the component placed in the bottom of the VA, has been selected to endure these kinds of hits. Therefore, this criterion is fulfilled.

In Table 9.4, the installation and maintenance criteria together with their degree of fulfilment are listed. All these criteria have been fulfilled due to the position and geometry of the concept. The VA could be demounted from the sub frame if service is needed and other components that could be needed to be demounted for service or maintenance will not be affected by the position of the VA. It will be possible to install the VA in-house, meaning it could be installed in the vehicle in Volvo’s factories. In the end of the life time, the VA needs to be disassembled. Therefore, screws were chosen so that each material of the parts could be separated. In this way, the component could easily be disassembled.

Table 9.4: Degree of fulfilment for the installation and maintenance criteria.

Criteria	**Target value/specification**	**D/W**	**Degree of fulfilment**
3.1 Accessibility of VA	Reachable for service	W5	Green
3.2 Accessibility of vehicle components	Reachable for service	W4	Green
3.3 Installation	Possible in-house	D	Green
3.4 End of life time	Possible to disassemble	D	Green

In Table 9.5, manufacturing and assembly criteria together with their degree of fulfilment are listed. There are two criteria regarding manufacturing processes; one that the VA should be possible to manufacture; one that the manufacturing should be available in-house. The VA has been designed to be feasible to manufacture. However, it has not been verified that the VA will be manufactured in Volvo’s factories. The criteria *4.3 Number of components* has been fulfilled since the VA has been designed in as few number of components possible and still perform well for other criteria, such as being able to manufacture. The project has included design for assembly so that the design will allow for assembly. This assembly process could be done in-house and therefore, the criterion *4.4 Assembly processes* is fulfilled. The maximum manufacturing cost of the VA was stated to be 1 000 SEK. The manufacturing cost of the concept, excluding the cost of the electronics, was estimated to 572 SEK and therefore, this criteria is fulfilled.

Table 9.5: Degree of fulfilment for the manufacturing and assembly criteria.

Criteria	Target value/specification	D/W	Degree of fulfilment
4.1 Manufacturing processes	Be possible to manufacture	D	Green
4.2 Manufacturing processes	Available in-house	W2	Yellow
4.3 Number of components	As few as possible	W2	Green
4.4 Assembly processes	Available in-house	D	Green
4.5 Manufacturing cost	< 1 000 SEK	W4	Green

In Table 9.6, geometry and placement criteria together with their degree of fulfilment are listed. All criteria, except one, have been fulfilled. *5.3 Aerodynamic design* has not been prioritised since this was a low ranked wish. The standard SAE J2954 states different dimensions of the component depending on different coil ground clearances. This standard has been used as a guideline throughout the project and therefore the criteria *5.1 Ground clearance* and *5.5 Coil and ferrites volume* are fulfilled. The VA has been designed to fit in a low 60 series vehicle in the updated SPA platform, meaning that *5.2 Ground clearance* and *5.4 Platform* are fulfilled. The position of the VA was mainly decided to make as few critical modifications of vehicle components necessary. According to this, the criterion *5.6 Compatible with vehicle platform* is fulfilled.

Table 9.6: Degree of fulfilment for the geometry and placement criteria.

Criteria	Target value/specification	D/W	Degree of fulfilment
5.1 Ground clearance	Z2 = 140-210 mm	D	Green
5.2 Ground clearance	Cluster 60 low vehicle	D	Green
5.3 Aerodynamic design	Low flow resistance	W1	Red
5.4 Platform	Fit in updated SPA	D	Green
5.5 Coil and ferrites volume	260 x 380 x 21 mm^3	D	Green
5.6 Compatible with vehicle platform	Few critical modifications of vehicle components	D	Green

In Table 9.7, material criteria together with their degree of fulfilment are listed. All these criteria have been considered during the project. However, it has been difficult to verify if the criterion *6.4 Environmental friendly* has been fulfilled and therefore, more testing and analyses are needed to ensure a safe product for the environment. The other material criteria are fulfilled mainly due to the choice of materials of the different components of the VA.

Table 9.7: Degree of fulfilment for the material criteria.

Criteria	Target value/specification	D/W	Degree of fulfilment
6.1 Corrosion	No change of material properties	D	Green
6.2 Chemical resistant	No change of material properties	D	Green
6.3 Water resistant	No change of material properties	D	Green
6.4 Environmental friendly	No/low impact on environment	W4	Yellow

In Table 9.8, non-functional criteria together with their degree of fulfilment are listed. These involves the total weight of the VA concept. The demand states a maximum weight of 15 kg, while the wish states a maximum weight of 12 kg. The total weight of the VA has been estimated to almost 7 kg excluding the electronics. This means that the electronics could weigh 5 kg and still fulfil the wish.

Table 9.8: Degree of fulfilment for the non-functional criteria.

Criteria	**Target value/specification**	**D/W**	**Degree of fulfilment**
7.1 Total weight	< 15 kg	D	Green
7.2 Total weight	< 12 kg	W3	Green

In conclusion, the majority of the criteria are considered being fulfilled. The lack of details concerning electronics in the concept resulted in that not all criteria could be verified. However, the component is designed to make room for all the necessary electronics. With further development and refinement, all the criteria could be fulfilled.

10 Discussion

In this chapter, a discussion of the work accomplished is conducted. Methods as well as results from the process are critically discussed.

Regarding the relevance of the task, the technology and competitor benchmarking indicated a trend towards implementation of wireless charging. However, the maturity of the technology in a vehicle could be questioned since no competitors have yet released a component for 11 kW inductive charging, the charging time is long, and the cost is high. Despite this, Volvo Cars needs to consider an implementation and make space for the component in their future electric vehicle platforms to maintain their competitive position. In addition, the company offers cars within the premium segment and has customers with high expectations and needs of using the newest technology. These customers could possibly be willing to pay which even more proving the importance of offering this kind of technology. Even though the project only resulted in a conceptual idea, the idea could help and direct the company of how the further development and implementation could be carried out. Therefore, the relevance of the task was considered being high.

The project group's mechanical background together with a master within product development suited the project well. The methodology was inspired by the generic product development process described in Product Design and Development (Ulrich & Eppinger, 2012), with some modifications and complementary material. The order of the tasks ensured that a certain level of knowledge and information was gathered before entering a new phase. However, iterations between the phases were needed since new information arose during the project. The matrices used for evaluation and elimination ensured that the project went in right direction since all ideas were evaluated based on the requirement specification. However, it is a risk of basing all decisions on matrices. This since, if not right criteria are included in the requirement specification, the matrices could show incorrect result. The project group tried to avoid this by not base the final decision exclusively on the matrices. Instead, evaluations within the project group as well as with experts within the fields of relevance were conducted at the final stages of decisions. However, the requirement specification was made with the knowledge gained and there is a risk that some criteria were excluded which could have change the result of the project. For instance, how the aerodynamic of the car was affected for each concept was not investigated.

The problem decomposition laid the foundation for the development process. It included important tasks which ensured that a certain level of knowledge about the technology was achieved, and that the project group had the same perception about the task. However, the stage had most focus on the mechanical parts and the electronics were only touched upon. The limited knowledge about electrification resulted in several assumptions during the project. For instance, how the integration with the OBC could work in theory is only described in the project, but no details are defined. It followed by an assumed volume reduction of 40 % of the electronics, which mainly was made by the project group together with the department of electrification at Volvo Cars. However, if more knowledge about electrification had been achieved, a more detailed level of the integration could possibly be reached. On the other hand, the limited knowledge could possibly have resulted in more freely thinking, leading to that more creative ideas were generated which neither Volvo nor their suppliers have thought about before.

As mentioned, it was decided to integrate the VA with the OBC. In this way, components could be eliminated from the VA and instead utilise components in the OBC. This will lead to volume and possibly cost reduction of the VA. However, there is a risk that the OBC instead will grow in size and become more expensive. This since the OBC must be modified to be adapted with the wireless charging technology. In addition, the OBC needs to be more robust and more software will be needed to, for instance, prevent the plug-in and wireless charging system to charge the vehicle battery simultaneously to eliminate risk for overload. Despite these consequences, the integration has several opportunities. Since the OBC is a component needed for charging the battery, it could be beneficial to centralise the both charging methods. Also, the number of components and volume for the entire platform could possibly be reduced. This since the VA will utilise most of the components already present in the OBC.

Due to the limited time of the project, only a conceptual component was developed. It was therefore difficult to ensure that all demands in the requirement specification were fulfilled. For instance, the strength and the components behaviour in collision could not be verified. However, in this project, the requirement specification had the purpose of guiding decisions towards a product which, with further work, will fulfil all demands. Therefore, the requirement specification had a central role and was critical for the result.

The project was mainly divided into two parts, positioning and geometry determination. The position was decided based on the knowledge about the platform at that stage in the process. The concept was later developed to best suit the selected position with as few modifications of existing components as possible in mind. However, it would be interesting to study if the result had been the same if the tasks were executed in reverse order. In that case, a geometry which is optimal for the wireless charging process could be developed and thereafter the position be selected based on that geometry. However, the selected order of the tasks seemed relevant due to the difficulties of finding a proper position, and the importance of keeping the ground clearance.

Since the technology is new within the automotive industry, it would be beneficial to have a modular product which easily could be modified if new trends arose. For instance, if competitors will release wireless charging with a higher power input, it would be beneficial if Volvo Cars rapidly could adapt their system to the new trend. According to the recommended practise SAE J2954, increased power input would mainly result in larger dimensions in x and y direction for coil and ferrites, which is not possible to change in the developed concept without modifications in the platform. However, the most critical dimension was found to be in z direction due to the ground clearance. The dimensions in z direction would only change a little if the power input increases. This will ease the adaption to higher power input.

11 Conclusion

In the chapter, the most important findings are presented. They are presented in chronological order according to the report.

The patent and benchmark searches gave indications of trends and possibly future standards regarding wireless charging. Competitors such as BMW and Audi will probably launch their technology this year, and the number of patents mostly increasing year by year. Two main coil topologies dominates the market, and their intellectual property needs to be bought if using them. The most important findings from the searches were:

- Trend of position the VA in the front, under the car
- Power input of 11 kW are needed to become competitive within the field
- Two coil topologies dominates the market: Double D and Circular design

The problem decomposition resulted in a requirement specification consisting of 39 criteria. A volume of the coil, ferrites and surrounded housing was stated by the recommended practice SAE J2954 for ensuring an efficient energy transfer. Complementary, the platform had limited space together with ground clearances which were needed to be considered. During the development of the position and geometry, the following requirements were considered to be most critical:

- Fixed volume of coil, ferrites and surrounded housing
- Limited space in the platform

By generating and evaluating ideas with both customer and company needs in mind, the optimal position resulted to be on the front sub frame, under the car. The position resulted in few modifications of vehicle components, good attachment possibilities, high wireless charging efficiency, convenient manoeuvring of the car and possibilities to protect the vehicle assembly. Due to the limited space, the vehicle assembly was positioned at ground clearance and a cut out in the sub frame was needed to fit the component. The vehicle assembly was designed to minimise modifications on the sub frame as well as surrounding components by position the electronics, screw attachments and connectors in a proper way. However, the electronic volume had potential to be decreased. The on-board charger, an already existing component in the platform used for conversion of current for the plug-in system, could be utilised for this purpose. The integration resulted in an elimination of the rectifier, cooling system and current and voltage sensors in the vehicle assembly. The volume of the electronics in the vehicle assembly was assumed to be reduced by 40 %. However, several components could be utilised to fulfil the demands of the component. The undershield of the platform could, with modifications, be used as an aluminium cover to protect surrounding components from magnetic field exposure. The existing undershield is produced in plastics, but ideas of changing the entire shield or parts of it to aluminium, or put on an aluminium coating were suggested. In summary, the suggested design of the vehicle assembly is as follows:

- Position on front sub frame, at ground clearance
- Double D coil topology
- Single box solution with electronics and connectors positioned in front
- Integrated with on-board charger
- Undershield working as protection shield.

12 Recommendations for Further Development

The VA developed is considered to be at a conceptual stage and further development is needed before manufacturing and launching the wireless charging system. The chapter describes some of the improvements needed and the order of the recommended future work.

First of all, Volvo Cars needs to perform strength calculations, for instance finite element analyses. The concept and its fasteners need to manage vibrations and its own load during the entire life time. Presumably, material can be removed or added on different places depending on the result of the analyses. It could also be of interest to examine and optimise the number of screws needed. Some screws could presumably also be replaced by snap fasteners which could ease the assembly process even further. Even though the VA was developed with few modifications on the sub frame in mind, supporting structure needs to be added to the sub frame for reinforcements. Analyses are recommended to ensure that the strength of the sub frame is remained.

The next step is then to share the outer geometry with their suppliers. The geometry could be used as a design guideline for the suppliers since Volvo Cars know it fits the platform in an optimal way. Suppliers can try to develop something similar which then should be tested in the platform for evaluations. The developed concept should include the electronics needed. First, a virtual prototype should be used for analysis. When the most critical modifications have been made, a physical prototype is suitable to use. When it is ensured that the physical prototype fits in the platform, the aerodynamics and electronic interference of the component should be analysed. These were two of the criteria not yet verified in the requirement specification due to the detailed level of the concept. The aerodynamics should be analysed by suppliers while the electronic interference needs to be analysed at Volvo Cars due to the system level of the criteria. Thereafter, the criteria not verified for life time and collision safety should be analysed. The life time should be verified with environmental tests by suppliers, while collision safety needs to be investigated by Volvo Cars. Volvo Cars needs to verify collision since the entire platform needs to be tested.

Later on in the development, the positioning of the OBC should be investigated. To fully utilise the potential of the integration, recommendations of placing the OBC in the front of the car, near the VA, are suggested. It would result in shorter transportation of HV, meaning possibly higher efficiency for the total wireless charging system. However, the plug-in system is already utilising the OBC. Without knowing where this system will be positioned in the future, it is recommended to also position this system in the front of the vehicle.

At the same time, investigations of integrating even more electronics to the OBC should be made, together with analyses of the consequences of the modifications. Regarding the coil and ferrites, both geometries could be even more optimised and a fastening solution developed. The Circular and Double D coil topology were analysed in the project, but each topology has different variants which are also needed to be investigated. Complementary, the direction of the coil needs to be analysed to ensure that the VA will be compatible with a possibly future standard GA.

The project focused on implementing the VA in the SPA platform. However, Volvo Cars is also using the CMA platform for their smaller models. No investigations have been made of how this implementation could be made in the CMA platform, but the project group recommend to do so. It would be beneficial if the component could be implemented in a similar way, and that parts could be shared between the platforms.

Since the technology involves magnetic field, it is of high relevance to examine the exposure of magnetic field in such a system. Again, it was difficult to undertake such an investigation due to the detailed level of the concept, meaning that the concept developed did not include the necessary electronics. However, the standard SAE J2954 suggests how such an analysis could be performed and it is recommended to follow its guidelines. The analysis should also include how the undershield could be used as a protection shield in an optimal way. A new design is presented in the project, but only ideas of how the aluminium could be put in place. The ideas could, however, be used for analyses when developing the protection shield.

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Appendix A – Patents

A1 – Search approach for landscape searches

Search	Search string	Classification	Hits
Inductive charging, general	(inductive OR wireless) AND charg*	H02J50/00	508
Inductive charging, vehicle	(inductive OR wireless) AND charg* AND vehicle	B60L, H02J	175

A2 – Search approach for screening searches

Search strings used and number of hits for each search, when answering the question to the problem about having a cord to plug-in

Keywords used	Classes used	Search query/string	Hits
Inductive, wireless, charging, vehicle	B60L, H02J50	(Inductive OR wireless) AND charg* AND vehicle	52
Inductive, wireless, charging, electric, vehicle	B60L, H02J50	(Inductive OR wireless) AND charg* AND electric* AND vehicle	37
Inductive, charging, vehicle, electric	B60L, H02J50	Inductive charging AND vehicle AND electric	6

Search strings used and number of hits for each search, when answering the question to the problem about not having enough space for the technology

Keywords used	Classes used	Search query/string	Hits
Wireless, charging, vehicle, battery, electric		**Title:** wireless AND charg* AND vehicle **Abstract:** battery AND electric	112
Wireless, charging, vehicle, battery, electric, induction	B60L, H02J	**Title:** wireless AND charg* AND vehicle **Abstract:** battery AND electric AND induct*	10

A3 – Summary of patents found

<table>
<tr><th>CN106994908 (A)</th><th>Sections of relevance in prior art</th><th>Subject features fulfilled</th></tr>
<tr><td>Wireless charging device and charging method for vehicle
Inventor: Xue Chenguang, Lu Jun, Guo Xiaojun
Applicant: Rayspower Energy Group Co Ltd
Priority filing date: 2017-04-24</td><td>"The charging device comprises an electromagnetic transmitting coil, an electromagnetic receiving coil installed on the lower portion of a vehicle chassis, an omnidirectional moving trailer and a positioning device"

https://worldwide.espacenet.com/publicationDetails/biblio?DB=EPODOC&II=4&ND=3&adjacent=true&locale=en_EP&FT=D&date=20170801&CC=CN&NR=106994908A&KC=A#</td><td>The interesting part of this invention is the geometry of the receiving coil, how it is installed on the vehicle, and how the induction technology works.</td></tr>
<tr><th>CN105186611 (A)</th><th>Sections of relevance in prior art</th><th>Subject features fulfilled</th></tr>
<tr><td>Inductive charging vehicle having automatic positioning
Inventor: Shinji Ichikawa
Applicant: Toyota Motor Co Ltd
Priority filing date: 2010-03-16</td><td>"An electric vehicle receives electric power, in a non-contact manner, from an electric power transmitting coil provided externally to the vehicle. The electric vehicle includes an electric power receiving unit that is disposed at a bottom of the vehicle and receives electric power from the electric power transmitting unit via electromagnetic field resonance..."

https://worldwide.espacenet.com/publicationDetails/biblio?DB=EPODOC&II=37&ND=3&adjacent=true&locale=en_EP&FT=D&date=20151223&CC=CN&NR=105186611A&KC=A#</td><td>A similarity are that an electric vehicle receives power wirelessly from an external transmitting coil. A feature in this invention which will not be included in the project is that a camera captures the outside environment and a display unit inside the vehicle that shows the environment the camera captures.</td></tr>
<tr><th>JP2015208222 (A)</th><th>Sections of relevance in prior art</th><th>Subject features fulfilled</th></tr>
<tr><td>Inductive charging system for electric vehicle
Inventor: David W Baarman, Sean T Eurich, William T Stoner Jr, Joshua B Taylor, Richard J Weber
Applicant: Access Business Group Int Llc
Priority filing date: 2010-01-05</td><td>"The system includes the primary coil that is recessed below a surface supporting a vehicle and is protected by a cover. The secondary coil is protected and supported by a sliding plate mounted to the vehicle. The system includes a charging circuit that is controlled by signals transmitted by a garage door opener transmitter or a garage door opener. The system includes sensors that detect presence of an animal or an object in a space between the primary coil and the secondary coil."

https://worldwide.espacenet.com/publicationDetails/biblio?DB=EPODOC&II=38&ND=3&adjacent=true&locale=en_EP&FT=D&date=20151119&CC=JP&NR=2015208222A&KC=A#</td><td>The invention includes a wheel chock that raises the transmitting coil into alignment with the receiving coil. Such a system is not included in this project. However, the system also includes sensors that can detect if an object or animal is in between the two coil. This could be of interest when developing with safety in mind.</td></tr>
<tr><th>US2016176299 (A1)</th><th>Sections of relevance in prior art</th><th>Subject features fulfilled</th></tr>
<tr><td>Protective shield for an electric vehicle inductive charging pad
Inventor: Kautz Richard William
Applicant: Ford Global Tech Llc
Priority filing date: 2014-12-18</td><td>"A vehicle includes a vehicle coil assembly configured to couple with a ground coil assembly in a presence of a magnetic field there between for wireless power transfer to the vehicle. The vehicle coil assembly includes an inflatable shield configured to extend from the vehicle and form a barrier around a portion of the magnetic field."

https://worldwide.espacenet.com/publicationDetails/biblio?DB=EPODOC&II=1&ND=3&adjacent=true&locale=en_EP&FT=D&date=20160623&CC=US&NR=2016176299A1&KC=A1#</td><td>This invention could be of interest if examining safety regarding exposure of electromagnetic fields.</td></tr>
</table>

WO2016173863 (A1)	**Sections of relevance in prior art**	**Subject features fulfilled**
Antenna, inductive charging device, electric vehicle, charging station, and inductive charging method **Inventor:** Kurz Fabian, Müller Dominikus Joachim, Müller Reiner **Applicant:** Siemens Ag **Priority filing date:** 2015-04-30	"The invention further relates to an inductive charging device, an electric vehicle, a charging station, and an inductive charging method..." https://worldwide.espacenet.com/publicationDetails/biblio?DB=EPODOC&II=0&ND=3&adjacent=true&locale=en_EP&FT=D&date=20161103&CC=WO&NR=2016173863A1&KC=A1#	The invention includes an inductive charging method for an electric vehicle which could be of interest to investigate.
CN104539008 (A)	**Sections of relevance in prior art**	**Subject features fulfilled**
Electric vehicle road wireless charging system **Inventor:** Cao Yijia **Applicant:** Cao Yijia **Priority filing date:** 2014-12-18	"The invention relates to an electric vehicle road wireless charging system which comprises an electric vehicle and a road charging device. An electromagnetic induction receiving device and an induction device are arranged at the bottom of the electric vehicle." https://worldwide.espacenet.com/publicationDetails/biblio?DB=EPODOC&II=9&ND=3&adjacent=true&locale=en_EP&FT=D&date=20150422&CC=CN&NR=104539008A&KC=A#	This invention is in some way out of scope of the project since the vehicle can be charged without being parked. However, to get an insight of this invention, one can get a perception of how the vehicle could be charged efficiently while driving in the future.

Appendix B – Requirement Specification

B1 – Final requirement specification

	Criteria	Target value/Specification	D/W	Weight (1-5)	Verification method	Stakeholder
Requirement Specification						*Created:* 2018-02-02 *Modified:* 2018-05-09
Function						
Transform magnetic field into DC from GA to vehicle battery						
1.	**Performance**					
1.1	Power input	11 kW	D		Performance test	Market analysis + Volvo Cars
1.2	Power efficiency	> 90 %	D		Performance test	Market analysis + Volvo Cars
1.3	Operational temperature	-40°C to 85°C	D		Environmental test	Volvo Cars
1.4	Life time	> 15 years	D		Fatigue test	Volvo Cars
1.5	Life time	> 5 475 cycles	D		Fatigue test	Volvo Cars
1.6	Operating frequency	85 kHz	D		Performance test	SAE J2954
1.7	Strength	Manage its own load	D		FEM simulation	Volvo Cars
1.8	Collision safety	No open electrical circuit	D		Collision test	Volvo Cars
1.9	Collision safety	Not affecting the deformation behaviour negatively	D		FEM simulation	Volvo Cars
2.	**Functional**					
2.1	Electronic interference	Not being disturbed by electronics	D		Functional test	SAE J2954
2.2	Electromagnetic compatibility	Not disturb electronics surrounding	D		Functional test	SAE J2954
2.3	Exposure of magnetic field	Not affect living beings	D		Functional test	SAE J2954
2.4	Leakage proof	No moisture inside component	D		Environmental test	Volvo Cars
2.5	Driving performance	Not affected negatively	D		User test	Volvo Cars
2.6	Customer experience	Not affected negatively	D		User test	Volvo Cars
2.7	Compatible with critical vehicle components	VA not affecting negatively	D		3D modelling	Volvo Cars
2.8	Manage misalignments	High efficiency when misaligned	W	5	Functional test	Volvo Cars
2.9	Impact resistant	Withstand bumps and scratches	D		Functional test	Volvo Cars
3.	**Installation and maintenance**					
3.1	Accessibility of VA	Reachable for service	W	5	3D modelling	Volvo Cars
3.2	Accessibility of vehicle components	Reachable for service	W	4	3D modelling	Volvo Cars
3.3	Installation	Possible in-house	D		Consult with experts	Volvo Cars
3.4	End of life time	Possible to disassemble	D		Assembly test	Project group
4.	**Manufacturing and assembly**					
4.1	Manufacturing processes	Be possible to manufacture	D		Consult with experts	Volvo Cars
4.2	Manufacturing processes	Available in-house	W	2	Consult with experts	Volvo Cars
4.3	Number of components	As few as possible	W	2	3D modelling	Volvo Cars
4.4	Assembly processes	Available in-house	D		Consult with experts	Volvo Cars
4.5	Manufacturing cost	< 1 000 SEK	W	4	CES EduPack	Project group
5.	**Geometry and placement**					
5.1	Ground clearance	Z2 = 140-210 mm	D		3D modelling	SAE J2954 + Volvo Cars
5.2	Ground clearance	Cluster 60 low vehicle	D		3D modelling	Project group
5.3	Aerodynamic design	Low flow resistance	W	1	Simulation	Project group
5.4	Platform	Fit in updated SPA	D		3D modelling	Volvo Cars
5.5	Coil and ferrites volume	260 x 380 x 21 mm3	D		3D modelling	SAE J2954
5.6	Compatible with vehicle platform	Few critical modifications of vehicle components	D		3D modelling	Volvo Cars
6.	**Material**					
6.1	Corrosion	No change of material properties	D		CES EduPack	Volvo Cars
6.2	Chemical resistant	No change of material properties	D		CES EduPack	Volvo Cars
6.3	Water resistant	No change of material properties	D		CES EduPack	Volvo Cars
6.4	Environmental friendly	No/low impact on environment	W	4	CES EduPack	Project group
7.	**Non-functional**					
7.1	Total weight	< 15 kg	D		3D modelling	Volvo Cars
7.2	Total weight	< 12 kg	W	3	3D modelling	Volvo Cars

B2 – Weighting matrix

	2.8	**3.1**	**3.2**	**4.2**	**4.3**	**4.5**	**5.3**	**6.4**	**7.2**	**Σ**
2.8	X	0.5	1	1	1	1	1	0.5	1	**7.0**
3.1	0.5	X	1	1	1	1	1	0.5	1	**7.0**
3.2	0	0	X	1	0.5	0	1	0.5	0	**3.0**
4.2	0	0	0	X	0.5	0	1	0	0	**1.5**
4.3	0	0	0.5	0.5	X	0	1	0	0	**2.0**
4.5	0	0	1	1	1	X	1	0.5	1	**5.5**
5.3	0	0	0	0	0	0	X	0	0	**0.0**
6.4	0.5	0.5	0.5	1	1	0.5	1	X	0.5	**5.5**
7.2	0	0	1	1	1	0	1	0.5	X	**4.5**

0 – Less important
0.5 – Equally important
1 – More important

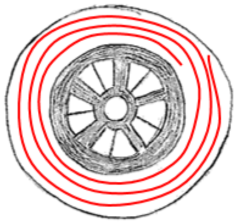
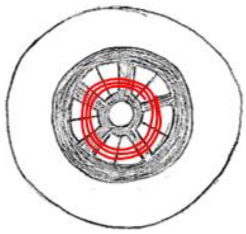
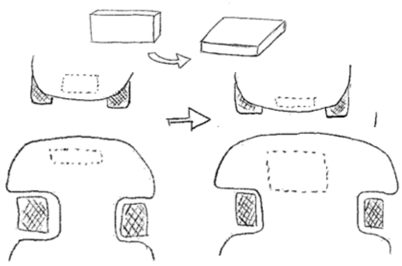
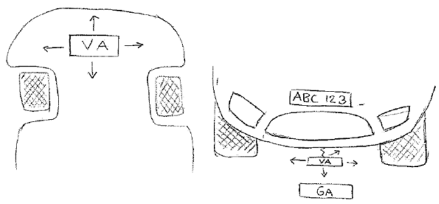
Appendix C – Positioning Pros and Cons Lists

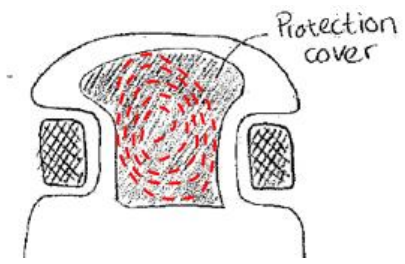
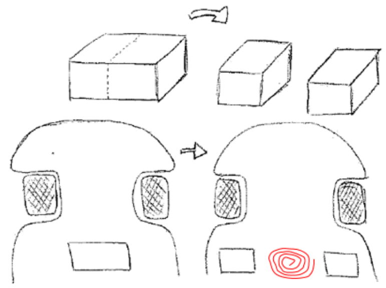
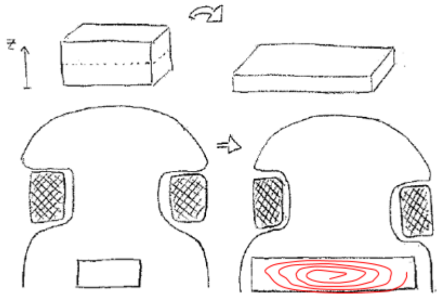
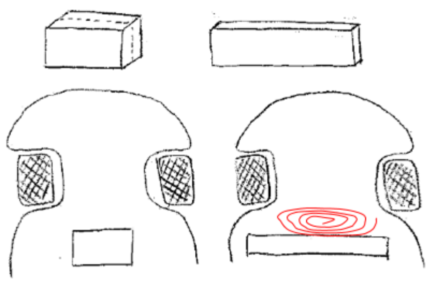
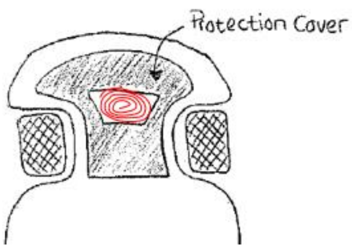
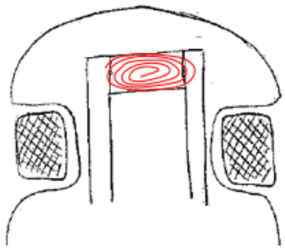
A1	A2	A3
+ Easier to position VA near GA + Market analysis predicts standard placement in this zone + Longer distance to driver and passengers - Could be less protected in collision - Limited space due to powertrain components	+ Enable parking from the front or behind + Market analysis predicts standard placement in this zone + Could be more protected in collision - Shorter distance to driver and passengers - Could be harder to position VA near GA - Lack of space due to batteries	+ Large space in trunk + Longer distance to driver and passengers - Could be less protected in collision - Could be harder to position VA near GA - Market analysis does not predict standard placement in this zone - Larger distance between car and the ground

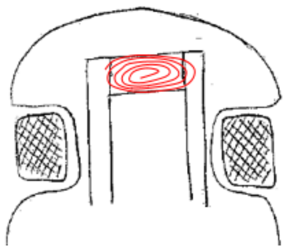
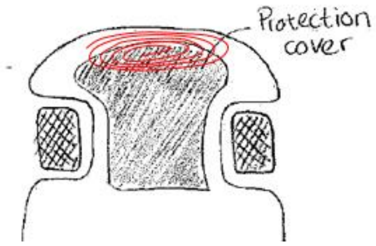
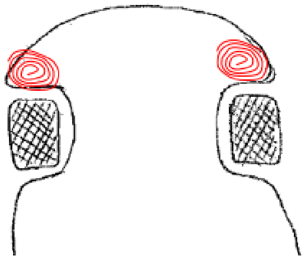
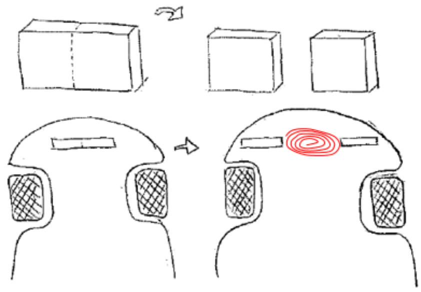
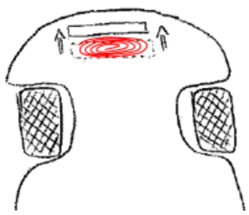
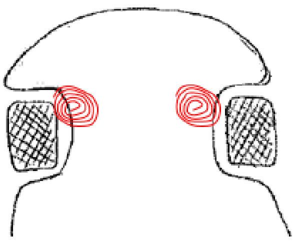
B1	B2	B3
- Could be harder to position VA near GA - Could be less protected in collision - Wheels may drive over GA when parking - More dynamic parts, could be harder to attach VA	+ Easier to position VA near GA + Market analysis predicts standard placement in this zone + Could be more protected in collision + Could have more attach points + Ease the parking	+ Easier to position VA near GA compared to B1 (if LHD) - Could be less protected in collision - Wheels may drive over GA when parking - More dynamic parts, could be harder to attach VA

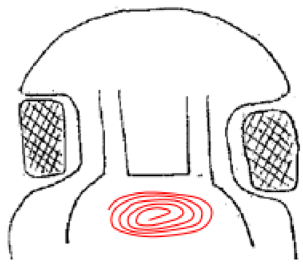
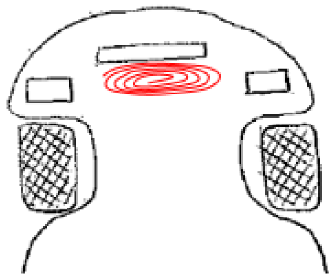
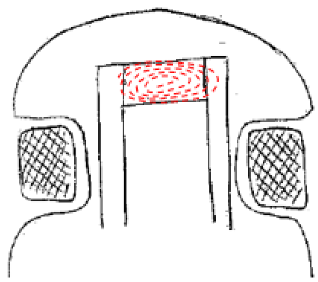
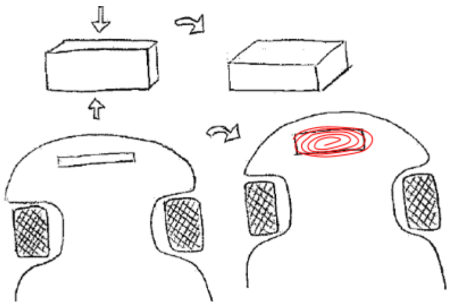
C1	C2	C3
+ Less electronics which may disturb/be disturbed + Possibility to connect VA with GA from above - Less attach possibilities - Shorter distance to driver and passengers - Could be less protected in collision - Installation of GA could be more demanding	+ More attach possibilities + Could be more protected in collision - Shorter distance to driver and passengers - More electronics which may disturb/be disturbed - Harder to connect VA to GA - Limited areas to attach VA - Installation of GA could be more demanding	+ Longer distance to driver and passengers + More attach possibilities + Could be more protected in collision + Possibility to connect VA with GA from below + More clear distance between ground and car base + Installation of GA could be easier - More electronics which may disturb/be disturbed

Appendix D – Summary of Positioning Concepts

#	Concept name	Description	Picture
1	*Wheels*	The concept uses the wheels for attachment. A coil is wired around/inside one or both of the front wheels. The GA needs to be placed on the sides.	
2	*Rims*	The concept using the rims for attachment. Coils are integrated in the front rims. The GA needs to be placed on the sides.	
3	*Air gap turner*	The concept is placed in front of the cooling system. When car is parked over GA, VA is precipitated down in z direction and rotated around y axis. When fully charged, the concept is rotated back to the front of the cooling system.	
4	*VA locates GA*	The concept is attached to the sub frame. Due to the size of the VA, the component is integrated in the sub frame and designed to carry load. When the car is parked, VA can move in x, y and z direction. The movements will be used to find the GA and connect to it. It is then possible to have the most effective charging process as possible.	
5	*Registration plate*	The coil is located on or inside the front registration plate. The GA is placed in front of the car when charging.	

6	*Undercarriage coil*	The concept uses the existing protection cover in the lowest part of the vehicle. A large coil covers the entire front under body of vehicle and is integrated in protection cover.	
7	*Battery Y*	The concept modifies a battery component in the vehicle. The component is divided in two in y direction and moved towards sides. The modification enabling space for VA between the two modified parts.	
8	*Battery Z*	The concept modifies a battery component in the vehicle. The battery component is cut in z direction, which makes battery longer in y direction and thinner in z direction. The modification enabling space for VA over the two modified parts.	
9	*Battery X*	The concept modifies a battery component in the vehicle. The battery component will be cut in x direction, which makes battery longer in y direction and thinner in x direction. Space will be enabled in front of the battery component.	
10	*Gap protection cover*	The concept uses a gap in the protection plate. The concept will be placed in the gap. Small modifications of the gap will be needed.	
11	*Below front sub frame*	The concept is placed in the space below the front sub frame, over the protection cover. The protection cover will be modified to handle the charging process.	

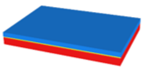
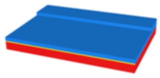
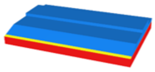
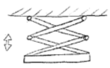
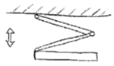
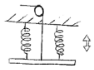
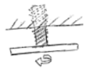
12	*Integration front sub frame 1*	The concept uses the front part of the front sub frame. The VA is integrated in the structure. The sub frame will be modified to keep its strength.	
13	*Below front undershield*	The concept utilise the space between undershield and protection cover. The VA is positioned between the components. The space is located far ahead in the car.	
14	*Front side gap*	The concept utilise the space in the front of the wheels, behind the lamps. The VA is divided into two parts, where each is position in the free space.	
15	*Cooling system split*	The concept modifies the cooling system in the front part of the vehicle. The component is divided in two in y direction and moved towards sides. The modification enabling space for VA between the two modified parts.	
16	*Cooling system moved*	The concept modifies the position of the cooling system in front of the car. The cooling system is moved further ahead, which enabling space behind where VA is be placed.	
17	*Wheelhouse space*	The concept uses volume available in front wheelhouse or nearby. It is possible to use both or one wheelhouse depending on the needed space for the VA.	

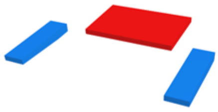
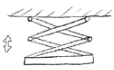
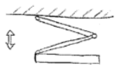
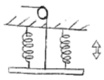
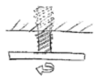
18	*Integration front sub frame 2*	The concept uses the rear part of the front sub frame. The VA is integrated in the structure. The sub frame will be modified to keep its strength.	
19	*Extra cooling system*	The concept modifies the existing cooling system. Two cooling radiators are added to the sides to reduce volume of existing cooling system. This making the cooling system smaller, which enables space for VA.	
20	*Below front sub frame*	The VA component is positioned in the space above front sub frame. When charging, the sub frame and protection cover will be placed between the VA and GA. The sub frame and protection plate will be modified to make the charging process efficient.	
21	*Cooling system squeeze*	The concept modifies the cooling system. The cooling system is squeezed in z direction. The change makes the cooling system thicker in x direction, which enabling space for the VA under it.	

Appendix E – Positioning Elimination Matrix

	Demands / Concept	Coil design fit into geometry	Compatible with GA	Collision - deformation	Modification of critical part	Distance to GA	Ground clearance	Further Development	Comments
1	Wheels	+	-					No	Could be difficult to make VA compatitable with GA. Damaged if wheel gets punctured
2	Rims	+	+	+	+	-		No	Could be difficult to make VA compatitable with GA due to the variation of vehicle width
3	Air gap turner	+	+	?	+	+	+	No	Further investigastions needed. Not possbile due to the air flow to the cooling system.Very unique for Volvo
4	VA locates GA	?	+	+	+	+	+	Yes	Further investigation about geometry is needed to ensure coil design fits. More advanced mechnical stucture and additional parts are needed due to the movements
5	Registration plate	-						No	Too small area for the coil design
6	Undercarriage coil	+	-					No	A large magnetic field will be generated which could be a problem for other components. A thicker protection cover is maybe needed which could affect the ground clearance. Could be very unique for Volvo
7	Battery Y	?	+	+	?	+	+	Yes	Further investigate the space around the battery. Need to invesigate the consequences of splitting the battery. Further consultation with battery experts
8	Battery Z	?	+	+	?	+	+	Yes	Further investigate the space around the battery. Need to invesigate the consequences of splitting the battery. Further consultation with battery experts
9	Battery X	?	+	+	?	+	+	Yes	Further investigate the space around the battery. Need to invesigate the consequences of splitting the battery. Further consultation with battery experts
10	Gap protection cover	?	+	+	+	+	?	No	Further investigation about geomery is needed to ensure coil design fits. Could affect ground clearance. No possible to cover the whole gap due to air flow. Redesign of shield is under development, will not look the same in the future
11	Below front sub frame	?	+	+	+	+	+	Yes	Further investigation about geomery is needed to ensure coil design fits. Investigate if the strength of the subframe could be affected
12	Integration front sub frame 1	?	+	?	?	+	+	Yes	Could be possible to integrate in subframe. VA could be dimensioned to carry load
13	Below front undershield	?	+	-				No	Further investigation about geomery is needed to ensure coil design fits. Could affect ground clearance. Could be hard to protect and follow the deformation in collision
14	Front side gap	?	+	-				No	Further investigation regarding geomery is needed to ensure coil design fits. The area could be sensitive in collision. Very unique for Volvo. Few attachments possiblilities. Hard to protect in collision, and affecting deformation
15	Cooling system split	?	+	?	-			No	Further investigation regarding geomery is needed to ensure coil design fits. The area could be sensitive in collision. Difficult and expensive to split. Not the same effect regarding air flow on the sides.
16	Cooling system moved	?	+	?	-			No	Further investigation regarding geomery is needed to ensure coil design fits. The area could be sensitive in collision. Difficult and expensive to split. Not the same effect regarding air flow on the sides.
17	Wheelhouse space	-						No	Too small area for the coil design
18	Integration front sub frame 2	?	+	?	?	+	+	Yes	Could be possible to integrate in subframe. VA could be dimensioned to carry load
19	Extra cooling systems	?	+	?	-			No	Further investigation regarding geomery is needed to ensure coil design fits. The area could be sensitive in collision. Difficult and expensive to split. Not the same effect regarding air flow on the sides.
20	Above front sub frame	?	?	+	+	-		No	Further investigation regarding geomery is needed to ensure coil design fits. Wireless connection could affect the subframe, e.g. getting too hot. Low efficiency, could be difficult to achieve sufficient distance to GA. Intresting aviable space, could be integrated in another concept
21	Cooling system squeeze	?	+	?	?	+	+	Yes	Further investigation regarding geomery is needed to ensure coil design fits. The area could be sensitive in collision. Investigate the consequences of squeezing the cooling system. Could affect deformation area in front. Further investaigations needed to ensure the same cooling efficency is achieved

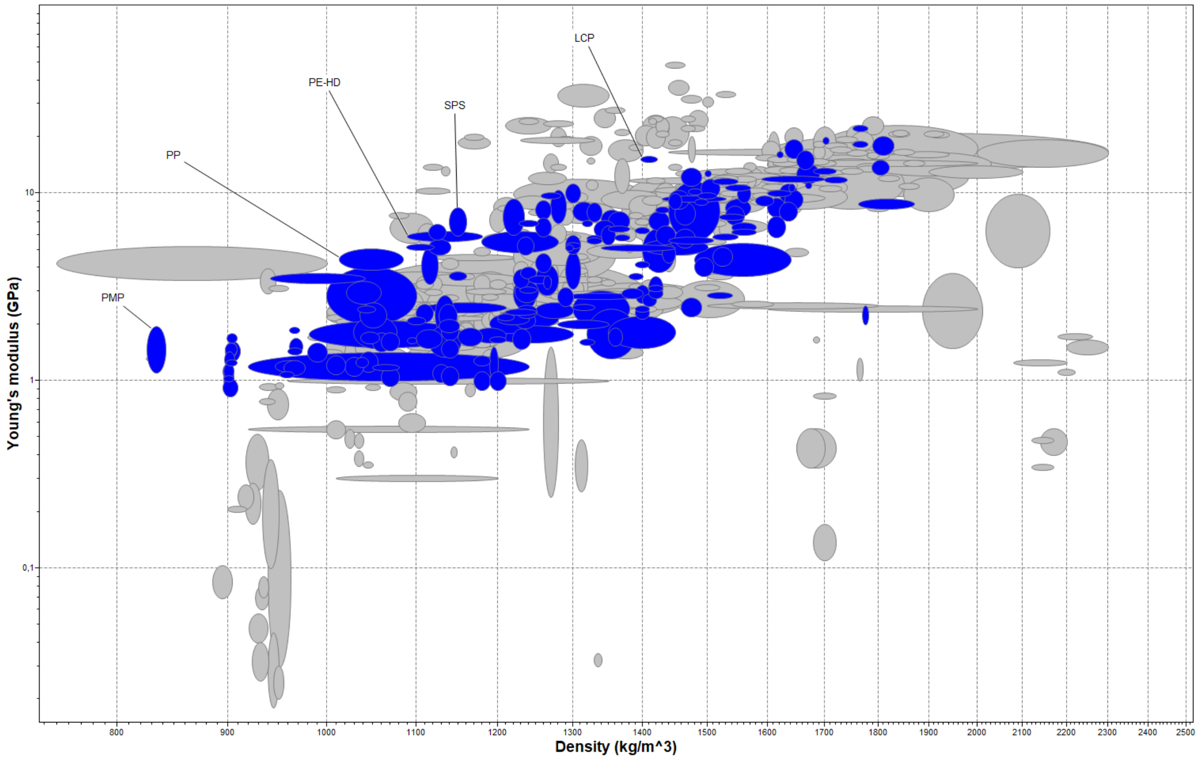
Appendix F – Morphological Matrices

One Box							
		A	B	C	D	E	F
1	Electronics geometry						
2	Coil house movement	Fixed					
3	OBC integration	Yes	No				

Multiple Boxes							
		A	B	C	D	E	F
1	Electronics geometry						
2	Coil house movement	Fixed					
3	OBC integration	Yes	No				

Appendix G – Material Selection

G1 – Material selection plot for plastic



G2 – Material Selection plot for metal