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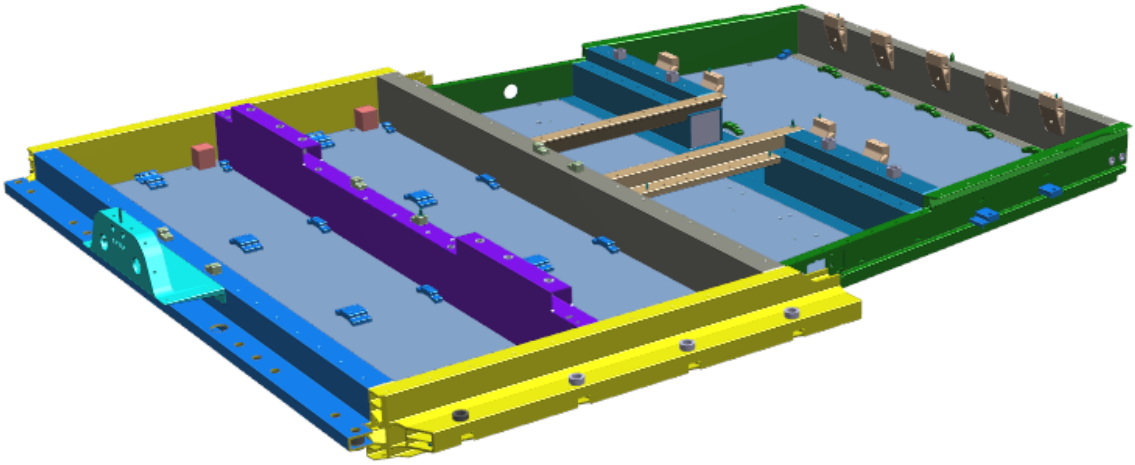

Design and Optimization of Battery Housing in Electric Cars

Master's thesis in Product Development

ABHISHEK BALA
MEHER CHAITANYA KAMARAJU

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

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Abhishek Bala
Meher Chaitanya Kamaraju

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Department of Industrial and Materials Science
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Abhishek Bala & Meher Chaitanya Kamaraju

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Academic supervisor and examiner: Kanishk Bhadani and Gauti Asbjörnsson, Department of Industrial and Materials Science, Chalmers University of Technology

Industrial supervisor and manager: Torbjörn Andersson, and Eva Haglund, Department of Vehicle Propulsion Geometry, Volvo Car Group

Department of Industrial and Materials Science
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone: +46 (0)31-772 1000

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Abstract

In the current market scenario, there is fierce competition in the automotive market as the market trend shifted towards the development of e-mobility and autonomous cars. The integration of advanced technology and battery modules increases the weight and cost of the battery pack which serves the background of the project. There is a need to reduce the weight and cost of the battery pack to achieve a long-range of the vehicle.

By investigating the opportunities in the battery pack, the scope was limited to battery housing components such as cross beams and bottom plates. In this thesis work, the product development approach was followed to redesign and optimize the existing battery housing of Volvo Cars in terms of weight reduction and material cost reduction with equivalent crash safety performance.

Various concepts on bottom plates and cross beams were generated from idea generation activities and using methods such as topology and topography optimization. Promising concepts were selected based on the parameters such as weight, material cost, manufacturing feasibility, and crash safety parameters (intrusion and bending) in the Kesselring matrix. The final concept has been obtained as a result of refinement and the simulations driven approach and has an opportunity to fulfill the requirements.

The final concept achieved 65.4% material cost reduction. There is also a possibility of merging many bottom plates in the existing concept into a few or single bottom plate with the help of the final concept. The extra weight of 6.3% and 28% intrusion loss of the final concept in comparison to the existing concept can be reduced if the final concept is redesigned. Hence, the steel material is found to be an opportunity for e-mobility to be affordable, cheaper, and sustainable in terms of environmental aspects.

Keywords: design, simulation, optimization, topology, topography, weight, cost, safety, product development, crash safety, battery pack, battery housing, battery electric vehicles.

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Abhishek Bala and Meher Chaitanya Kamaraju

Gothenburg, September, 2020.

Abbreviations

3D Three-dimensional

BEV Battery Electric Vehicle

BDU Battery Disconnect Unit

BMS Battery Management System

BTMS Battery Thermal Management System

CAD Computer Aided Design

CAE Computer Aided Engineering

CMA Compact Modular Architecture

HV High Voltage

DFM Design for Manufacturing

FEM Finite Element Method

FEA Finite Element Analysis

ICE Internal Combustion Engine

LWH Length Width Height

MEP Modular Electric Platform

NVH Noise Vibration Harshness

PCM Phase Change Material

PHEV Plug-in Hybrid Electric Vehicle

SEK Swedish krona

SOC State of Charge

SPA Scalable Platform Architecture

SWR Strength to weight ratio

TIM Thermal Interface Material

TO Topology Optimization

Contents

1 Introduction **1**
- 1.1 Company Background . . . 1
- 1.2 Project Background . . . 2
- 1.3 Aim and objectives of thesis work . . . 3
- 1.4 Project scope . . . 3
- 1.5 Project Delimitations . . . 4
- 1.6 Research Questions . . . 5
- 1.7 Report Outline . . . 5

2 Theory **7**
- 2.1 Battery Electric Vehicles . . . 7
- 2.2 Components of Battery pack . . . 8
  - 2.2.1 Cover lid . . . 8
  - 2.2.2 Bus Bars . . . 8
  - 2.2.3 Battery modules . . . 9
  - 2.2.4 Battery cells . . . 10
  - 2.2.5 Battery management system . . . 11
  - 2.2.6 BDU . . . 11
  - 2.2.7 Battery cooling system . . . 11
  - 2.2.8 Battery tray carrier . . . 12
- 2.3 Finite Element Analysis . . . 13
- 2.4 Crash Simulation . . . 14
  - 2.4.1 Importance of side pole test . . . 14
  - 2.4.2 Side pole: Worst case scenario . . . 15
- 2.5 Structural optimization . . . 15
  - 2.5.1 Topology Optimization . . . 16
  - 2.5.2 Topography Optimization . . . 17
- 2.6 Current trends in Industry . . . 17

3 Methodology **19**
- 3.1 Literature study . . . 20
- 3.2 Technological assessment . . . 20
  - 3.2.1 Interview guide and Knowledge transfer sessions . . . 20
  - 3.2.2 Competitors benchmarking . . . 20
  - 3.2.3 SWOT analysis . . . 21
- 3.3 Functional analysis . . . 21

3.4 Material study . . . 21
3.4.1 Materials benchmarking . . . 21
3.4.2 Materials selection . . . 21
3.5 Idea generation . . . 21
3.6 Topology Optimization . . . 22
3.7 Topography Optimization . . . 22
3.8 Concept evaluation . . . 22
3.8.1 Non-linear static simulation setup . . . 22
3.9 Simulations driven designs . . . 24

4 Technological assessment 25
4.1 Data collection from Interviews and Knowledge transfer sessions . . . 25
4.2 Competitors benchmarking . . . 25
4.3 Tesla Model 3 benchmark . . . 26
4.4 Chevrolet Bolt EV benchmark . . . 27
4.5 Jaguar I Pace benchmark . . . 27
4.6 Audi e Tron benchmark . . . 28
4.7 Energy density comparison . . . 29
4.8 SWOT Analysis for Battery Housing . . . 31

5 Requirements Specification and Functional Analysis 33
5.1 Requirements specification . . . 33
5.2 Functional analysis . . . 33
5.2.1 Identification of Functions for Battery Housing . . . 33
5.2.2 Black box model . . . 34
5.2.3 Process Flow Model . . . 34
5.2.4 Function means tree . . . 35

6 Material Study 37
6.1 Materials benchmarking . . . 37
6.2 Materials selection . . . 37
6.3 Environmental aspect . . . 39

7 Concept Development 41
7.1 Idea generation . . . 41
7.1.1 Brainstorming activity . . . 41
7.1.2 TRIZ method . . . 41
7.1.3 Morphological matrix . . . 42
7.2 Concepts generation . . . 42
7.2.1 Aluminium corrugated bottom plate . . . 42
7.2.2 Aluminium rectangular bottom plate concept . . . 43
7.2.3 Steel thin bottom plate concept . . . 43
7.2.4 Steel corrugated bottom plate concept . . . 44
7.2.5 T shape concept - Integrated cross beam and bottom plate . . . 44
7.2.6 I shape steel cross beam concept . . . 45
7.2.7 Rectangular shape cross beam concept . . . 46
7.3 Topology optimization driven concept generation . . . 46

7.4 Topography optimization . . . 48
7.5 Concepts evaluation . . . 48
7.5.1 Simulation of existing SPA2 reference model . . . 48
7.5.2 Simulation of Aluminium corrugated bottom plate concept . . 49
7.5.3 Simulation of Aluminium rectangular holes bottom plate concept . . . 50
7.5.4 Simulation of Steel corrugated bottom plate concept . . . 50
7.5.5 Simulation of Steel thin bottom plate concept . . . 51
7.5.6 Simulation of Steel T shape cross beam and bottom plate concept . . . 51
7.6 Simulation of topology optimisation driven concept . . . 52
7.7 Simulation of topography optimization driven concept . . . 53
7.8 Kesselring matrix . . . 54
7.9 Simulations driven design . . . 56
7.10 Transformation into the final concept . . . 56

8 Final concept **59**
8.1 Final concept description . . . 59
8.1.1 Design for Intrusion . . . 61
8.1.2 Design for Bending . . . 62
8.2 Manufacturing Plan . . . 62
8.3 Comparison : Existing vs. Final concept . . . 65
8.3.1 Safety evaluation . . . 65
8.3.2 Cost and weight analysis . . . 67
8.3.3 Machining and manufacturing lead time advantage . . . 68
8.3.4 Material advantages . . . 68
8.3.5 Sustainability aspect . . . 69
8.4 Fulfillment of requirements specification for final concept . . . 69

9 Discussions and conclusions **71**
9.1 Discussions . . . 71
9.1.1 Competitors benchmarking . . . 71
9.1.2 Materials study . . . 71
9.1.3 Concept development . . . 72
9.1.4 Optimization methods . . . 72
9.1.5 Simulations . . . 72
9.1.6 Opportunities for further development of final concept . . . 73
9.2 Conclusions . . . 75

10 Future work **77**

Bibliography **79**

A Appendix - Interview guide **I**

B Appendix - Competitors Benchmarking **III**

C Materials Benchmarking **VII**

D Appendix - Requirements specification **XI**

E Appendix - Idea generation **XIII**

E.0.1 Morphological Matrix XIII

E.0.2 Bottom plate dynamic concept for environmental conditions . XVI

E.0.3 Integrated sill beam and cross beam concept XVII

1
Introduction

This chapter involves the company background and project background. Furthermore, it discusses the aim, objective of the project, narrowing of scope to focus areas, delimitations, research questions, and the report outline.

1.1 Company Background

The Volvo Car Group is one of the premium car manufacturing company which is located in Sweden, with the headquarters in Torslanda, Gothenburg. It is a subsidiary of Geely Holding Group. Volvo Car is a global organization with the roots of Scandinavian, but manufacturing, research, and design operations are also located in Europe, Asia, and the America [1].

"For 2025, the business goals of Volvo Cars is to lead in electrification, safety, connectivity, and autonomous driving technology and assist the customer to move in a personal, sustainable, and safe way. With the goal of climate-neutral company by 2040, and reduce CO_2 emission by 40%, the company is driving towards electrification, and also focusing on every segment such as manufacturing, supply chain to reduce CO_2 with an aim of recycling and reuse of materials [1]".

In 1927, Volvo Cars started with the breakthrough invention of safety designing a three-point safety belt that saved a million lives. At present, the company is also leading in advanced passive safety like airbags, safety cages, spoc function, crumple zones, and active safety features such as city safety technology which includes Autobrake System, Oncoming Collision Mitigation, Steering Support, and Large Animal Detection and Evasion System [2] [3].

With safety and sustainability as the objective, Volvo Car Group is aiming to the integration of advanced technology in electric cars. They started with mHEV, PHEV and Battery Electric Vehicles. In the present scenario, Volvo Car Group have made significant investments in the design and development of Battery Electric Vehicle (BEV) due to growing levels of public concern over climate change and to meet the ambitious target for carbon emission reduction [4]. However, there are challenges in the battery electric vehicles, due to fierce competition in the market from the industries such as Tesla, Beijing Automotive Industry Holding Corporation Ltd., Renault-Nissan-Mitsubishi, BYD, SAIC Motor Corporation Limited, Chery Automobile Corporation Ltd as shown in figure 1.1.

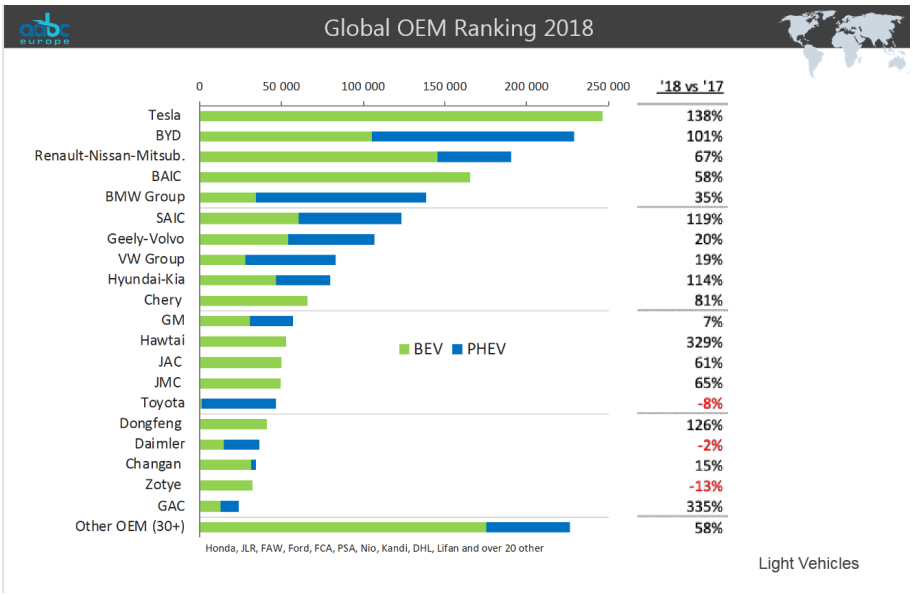

Figure 1.1: Global OEM Sales in 2018 [4]

1.2 Project Background

Generally, BEV is heavier due to more number of battery modules inside the battery pack which affects their performance. In the current scenario, Volvo Car Group will launch its first full-fledge BEV XC 40 Recharge which is CMA platform with battery pack weighing more than 500 kg, and energy capacity is 78 kWh with an estimated range of 400 km [5]. To improvise the range and aim towards larger vehicle segments, Volvo Car Group is developing an advanced platform called SPA2 as shown in the figure 1.2 [6]. The reduction of weight, material cost, and the packaging space with increasing safety in the battery system help in delivering compact and sustainable solutions to customers which serves the background for the thesis work. [Note: Figure 1.2 represents the CMA platform as it is confidential to reveal the complete details.]

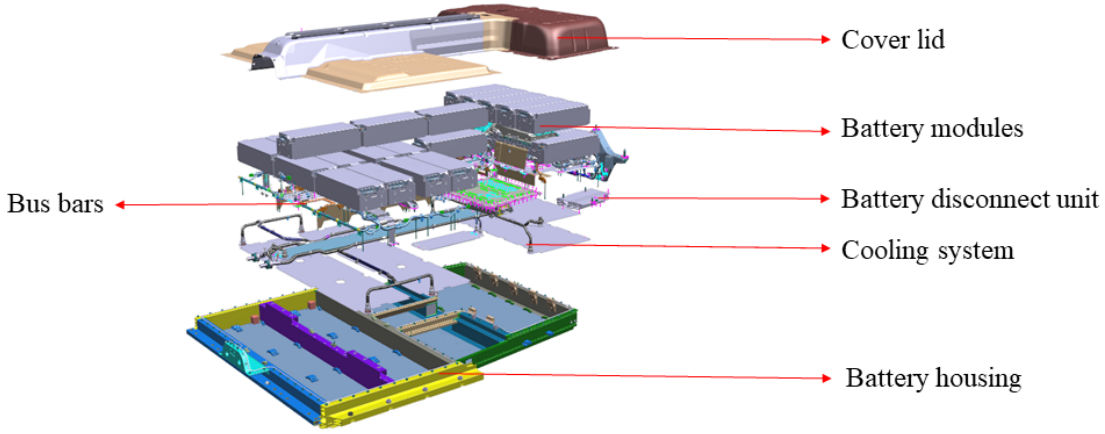

Figure 1.2: Battery pack of SPA2 platform [6]

1.3 Aim and objectives of thesis work

The aim of the thesis work is to optimize the existing geometry of SPA2 Battery housing. The major objectives of thesis work are

- to reduce material cost
- to reduce weight
- to have equivalent crash safety parameters as the existing battery pack.
- to provide a sustainable solution for the environment.

1.4 Project scope

The initial scope of the project was to examine the SPA2 battery pack and investigate opportunities serving the objectives of the thesis work. The SPA2 battery pack consists of several components such as battery tray carrier, cover lid, battery modules, module fixation, High Voltage (HV) components, bus bars, Battery Disconnect Unit (BDU), Battery Management System (BMS) and cooling system. However, we were requested not to look into the battery modules, as it was not manufactured by Volvo Car.

After investigating the opportunity in the battery pack, the scope was narrowed to battery housing structure (or battery tray carrier). The components of Battery housing structure are front and rear casting, bottom plates, sill beams and cross beams. However, because of limited time and in order to perform detailed analysis, furthermore narrowing down of scope to focus areas was necessary.

Based on weight breakdown analysis and interacting with engineers for potential opportunities, the project scope was narrowed down to few focus areas. In the weight breakdown analysis, bottom plate and cross beam were weighing heavier when compared to castings and sill beams as shown in 1.3. Additionally, sill beam and castings seemed to be engineered. Based on these factors, the authors found opportunities to reduce weight and material cost in bottom plates and cross beams. Hence, we selected our focus areas as SPA2 bottom plates and cross beams.

Bottom plates	Cross beams	Castings	Sill beam
31%	20%	22%	27%

Figure 1.3: Weight breakdown analysis of Battery housing

1.5 Project Delimitations

There were various choices followed in the thesis work to perform a detailed study in achieving the goals within 20 weeks.

- In this thesis work, complete car body and battery pack as a whole was not part of the study, instead the section of the battery pack was considered which is explained in detail in the section 3.8.1.
- The non-linear static structural simulation was conducted instead of dynamic simulation due to time constraint.
- The side pole crash load case was focused as this was the worst-case scenario for Bottom plates which was acted in between two Crossbeams acting directly on the bottom plates via through sill beam.
- The battery housing structure was simplified into a quarter section as this reduced the computational time for simulation.
- The access for information on manufacturing cost was limited due to confidential purpose instead, the focus was shifted to material cost.
- Joining methods and masses were not investigated in the study.
- The thesis work was narrowed to virtual development in software's such as Catia V5, Hypermesh (pre-processor), Optistruct (solver) and Hyperview (post-processor).

1.6 Research Questions

Based on the aim and objectives of thesis work, three Research questions(RQ) were stated below. The research and development in this thesis work were mainly aimed at addressing these three questions.

- RQ1 : What are various ways of achieving weight reduction in the existing components of battery tray carrier such as bottom plates and cross beams?
- RQ2 : What are the different ways of designing a structure that addresses side pole safety criteria of crash analysis set by Volvo Cars?
- RQ3 : How are the materials chosen for the design of components in the battery housing such as bottom plates and cross beams to reduce weight, cost and withstand crash loading?

1.7 Report Outline

The report starts with a brief introduction to this thesis work as well as the basic theory which will help the reader to understand the concepts which will be developed in further chapters. Thereafter the project is presented in chronological order of how it was conducted, starting with data collection activities, requirements specification, functional analysis, material study, concept development, and finally the presentation of the final concept along with conclusions. Future work and opportunities for the company are given at the end of the report.

2
Theory

This chapter outlines the basic theory to understand about the battery pack in an electric car and the components involved in it. It also involves a theory about finite element analysis and structural optimization. The supporting literature is also presented to discuss relevant studies carried out in the similar field of work.

2.1 Battery Electric Vehicles

To overcome the future challenges caused by the burning of fossil fuels (oil and coal) such as reduction of CO_2 emissions, climate change, increase of an interest in population towards environmental issues, the importance of electric vehicles has been increased in recent years [7].

The propulsion system in an electric vehicle consists of important components such as an energy storage device (battery system), electric machine, power electronics, and a portable charging device. The electric propulsion system is differentiated based on the architecture layout of the drive train (series, parallel hybrids) and range of hybridization (micro, mild, full, or plug-in hybrid). The energy storage device helps in determining the performance and range of the vehicle. They are differentiated by the type of chemistry involved in the device eg: lead-acid, nickel-metal hybrid or Lithium-ion battery, super-capacitor or hydrogen fuel cell which varies in their energy and power densities [7].

In comparison to other types of energy sources like gasoline, the batteries have significantly lower energy density. Hence the battery electric vehicle should contain several battery packs to maintain a suitable range for potential customers which in turn increases the weight of the vehicle. The battery system shall contain several different sub-systems like BMS, thermal management performance to deliver performance for the vehicle. The BEV have an electric propulsion system in which the electric machine replaces the IC engine as a single propulsion source. The electric machines are advantageous over IC engines as they have remarkable torque characteristics, high efficiency, high service life, low maintenance costs, and low noise level [7]. On the other hand, few challenges needs to be overcomed such as reduced range, increased initial cost, need for new charging, and recycling eco-systems. The advantages will over-weigh the challenges in the long-term meanwhile the issues such as cobalt mining, the toxicity of lithium which needs to be addressed in the future.

2.2 Components of Battery pack

The general descriptions about components of battery pack were discussed in this chapter along with details of SPA2 battery pack components. The exploded view of components is shown in figure 2.1

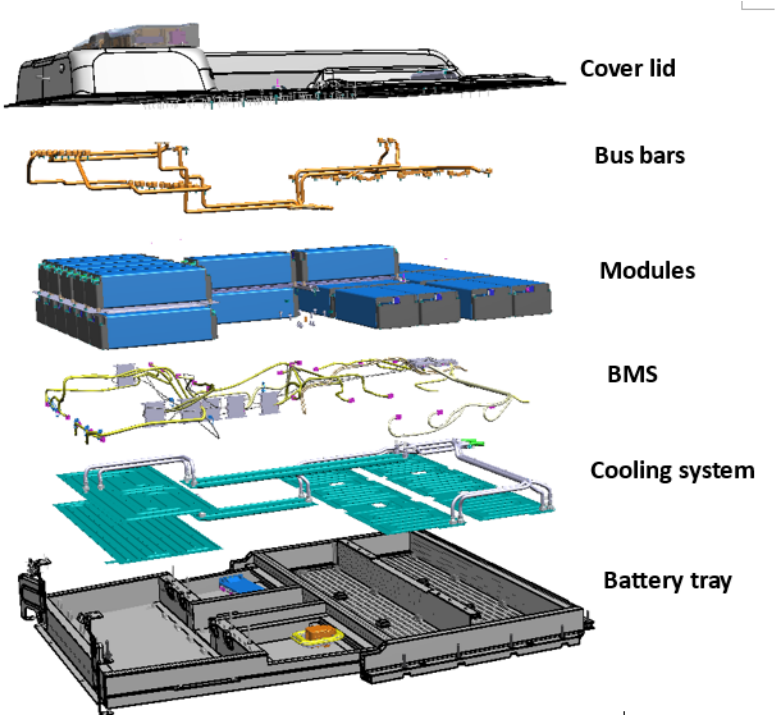

Figure 2.1: Volvo cars SPA2 battery pack [6]

2.2.1 Cover lid

The battery lid is the top portion of the battery enclosure and made usually of thin sheet metal as shown in figure 2.1. The battery lid is mounted on the battery tray carrier in such a way that it encloses all the components of the battery pack. The battery lid shall be gastight and shield the electro-magnetic current (EMC). Together with the tray, they are supposed to protect and prevent the ingress of particles and liquids. The lid is also supposed to make the internal components to access to assure that surrounding does not get in contact with high voltage. In the situation of the thermal event, the lid should be properly sealed to prevent heat and smoke to get into the compartment [8].

2.2.2 Bus Bars

The bus bars are the insulated high voltage power connections between the battery modules as shown in figure 2.2. They are usually made of copper and aluminum.

Generally, high voltage battery handles, conventional ordinary cables are used for high voltage applications. With a higher capacity of voltage, the cable needs to grow in diameter. Several aspects such as cost and package volume are likely the reasons for not using the wires. Bus bars that look like a rail serve this purpose which is used for distribution of voltage internally in the high voltage battery and to and from the connection for high voltage components. The flat shape and design flexibility of bus bars makes packaging efficient in the battery pack [8].

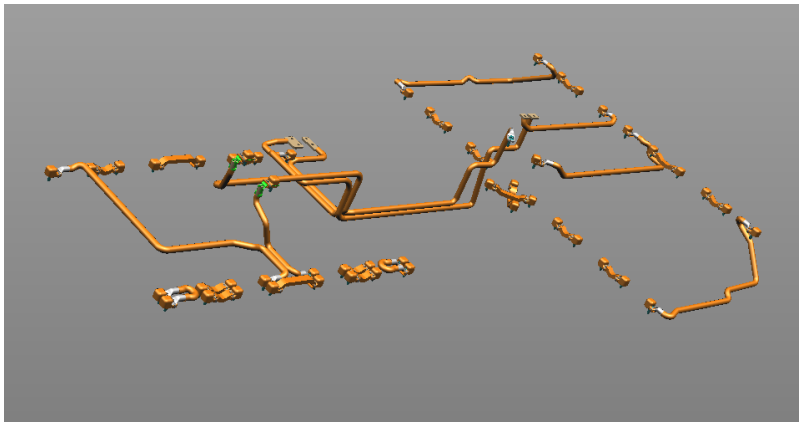

Figure 2.2: Bus bars [8]

2.2.3 Battery modules

The battery modules consist of several battery cells which form the main component of the battery system. The battery modules are built in such a way that it protects internal battery cells from external impacts and loads. The battery modules are connected in series to build up the voltage of 400 V [8]. The battery modules placed in the Volvo Cars SPA2 battery pack is shown in figure 2.3

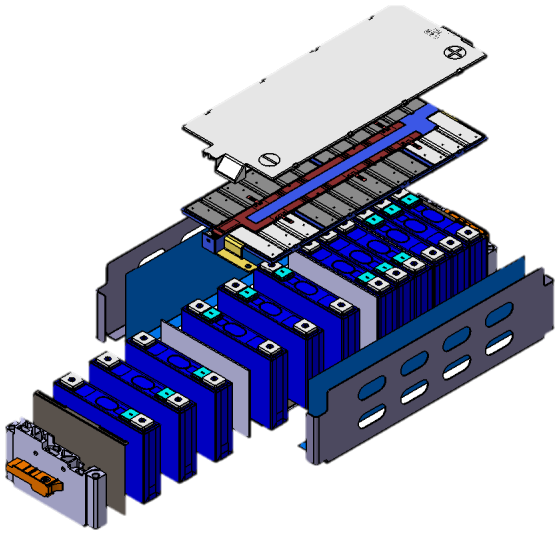

Figure 2.3: Volvo cars SPA2 modules [8]

2.2.4 Battery cells

Battery cells are the main component of the battery system and driver of chemical energy. The Battery cells have different types of cell chemistries like lithium-ion, lead-acid, nickel-metal hydride, etc. The battery cell also varies in geometry such as cylindrical cells, prismatic, and pouch cells [9]. The difference in properties between three types of cell geometries is represented in figure 2.4.

	Cylinder cell	Prismatic cell	Pouch cell
Energy Density	Medium	High	Highest
Mechanical Stability	High	Medium	Low
Thermal Performance	High	Highest	Medium
Space Utilization	Low	High	Highest
Manufacturing Cost	High	Medium	Low
Pressure withstand	High	Medium	Low

Figure 2.4: Different types of cell geometries [9]

2.2.5 Battery management system

The battery management system is the master control system for managing different slave units in the battery system. The BMS is the set of hardware and software and also a control module for battery safety monitoring. An intelligent Battery Management Unit (BMU) can control and manage cells individually, thus prolonging the lifetime, increasing the capacity, and managing the safety of the battery. The basic functionalities in a BMU consist of safety functions, voltage, and current measuring, SOC, and temperature monitoring [7].

2.2.6 BDU

BDU is called a battery distribution unit or battery disconnect unit. The Battery Disconnect Unit (BDU) usually contains the circuit breakers, current meter, electrical connectors, contactors, fuses, and the HV measurement points as shown in figure2.5. The BDU shall be accessible from inside the car to ease the service process. The main function is to safely connect or disconnect the battery from the vehicle HV bus in a controlled way. In the situation of overloading, it protects the HV bus components and vehicle from being destroyed by disconnecting the battery in the shortest possible time. All HV components and harness outside of the contactors are called HV bus. A BDU can have different designs and positions depending on the vehicle platform and application. It can be also placed both inside and outside the battery pack [8].

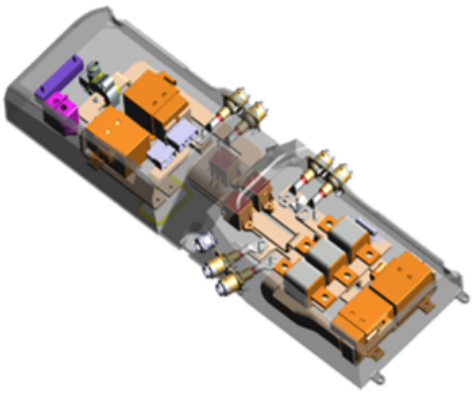

Figure 2.5: BDU [8]

2.2.7 Battery cooling system

The Battery cooling system is the core of battery performance and battery life. It helps in maintaining the operating ideal temperature of 15^0C to 30^0C in electric cars. The Battery cooling system is also known as the Battery Thermal Management

System (BTMS). The different types of BTMS technologies are air cooling, liquid cooling system, direct refrigerant cooling system, Phase Change Material (PCM) cooling system and thermoelectric cooling system as well as heating which is shown in figure 2.6

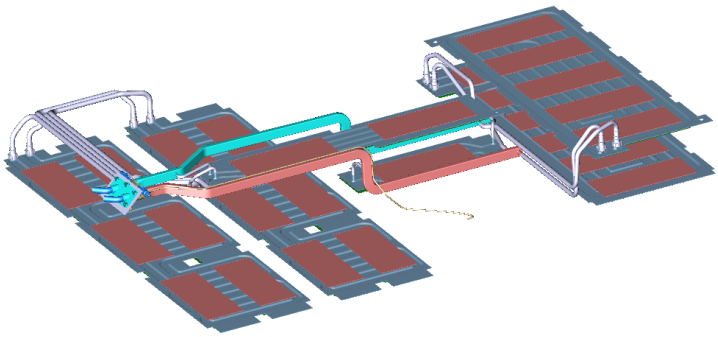

Figure 2.6: Volvo cars SPA2 cooling system [8]

Among different types of thermal management systems, the liquid cooling system is considered as it is widely used. The cooling system consists of cooling plates, inlet pipe, outlet pipe, distribution pipe and Thermal Interface Material (TIM). The main purpose of cooling plates is to cool the modules which are positioned on top of cooling plates. The coolant consists of 50/50 vol % ethylene glycol/water. The inlet pipe distributes cold water to the cooling plates. The outlet pipe removes the water that has been heated up by the modules. The distribution pipes transport cold water to thermal plates and heated water from plates. Since the surface of the thermal plate is uneven, thermal interference material is put to enhance heat transfer [8].

2.2.8 Battery tray carrier

The battery tray carrier in general carries and mounts the components of the battery systems such as modules, cooling systems, bus bars, and high voltage electronics. The battery tray is the bottom portion of the battery enclosure or housing. The battery tray carrier withstands and absorbs energy from the external impacts or loads such as structural loads. The battery tray is integrated with the chassis body. The size and shape of the battery housing are, on one hand, defined by the design space and the mounting points given by the vehicle and, on the other hand, by the internal components that have to fit in the housing. The module housing is designed to absorb the forces generated by the cells during operation. There are two reasons for this phenomenon. The first reason is the thermal contraction and expansion of the cells due to the changing temperature during operation. The second reason is the expansion and contraction of the lithium-ion cells, which are induced by the changing State of Charge (SOC) and state-of-health of the cells [7].

As shown in figure 2.7, the Volvo cars SPA2 battery tray carrier consists of compo-

nents such as crossbeam, bottom plates, sill beams, and castings in front and rear. All these components share a common feature of protecting the battery modules from crash loads and other intrusions into the tray carrier. The tray carrier consists of 5 cross beams which are situated between two sill beams. The cross beams are secondary safety components that protect the battery modules from crash load in the sideways direction. The tray carrier consists of 9 bottom plates which are situated at the bottom of the battery modules. The bottom plate is designed in such a way that there is no intrusion from the bottom of the car into the tray carrier and also designed according to environmental conditions. The sill beams are situated at the left and right ends of the tray carrier. They are primary components designed to withstand the sideways crash load. The castings are primary safety components that are situated in the front and rear side of the tray carrier, designed to withstand the crash load from the front and rear directions of the car.

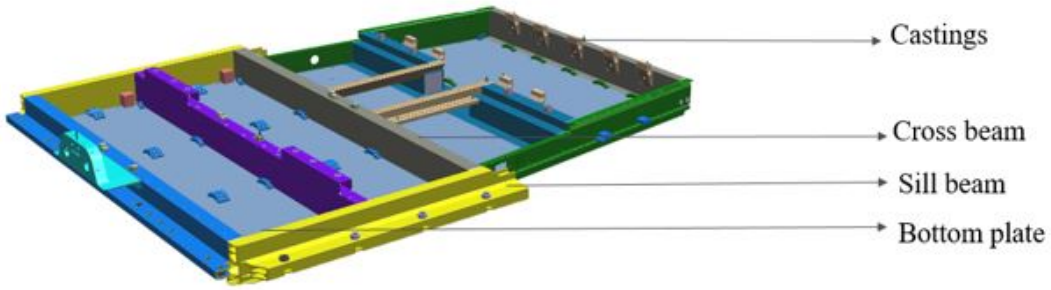

Figure 2.7: Volvo cars SPA2 tray carrier [6]

2.3 Finite Element Analysis

Finite Element Method (FEM) solves the partial differential equation which idealise the real model consisting of loads, boundary conditions, material and interprets the approximate solution. Finite Element Analysis (FEA) is a practical way to solve FEM problems which is represented in figure 2.8, it involves pre-processing, solution step, post-processing, and engineering judgements or evaluate the results [10].

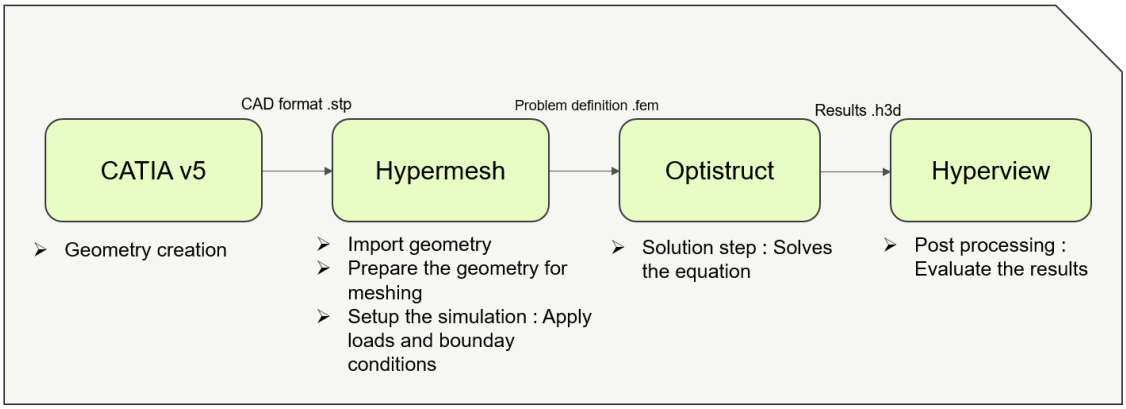

Figure 2.8: An overview of workflow from CAD geometry to evaluation

2.4 Crash Simulation

2.4.1 Importance of side pole test

Every year there is estimated 225,000 people are involved in side-impact collisions caused due to utility poles, guardrail terminals, and roadside objects for ICE vehicles. Such incidents cause 3 billion dollars yearly, injures one in three-vehicle occupant, and fatally injuries one in hundred as per the data submitted in the year 1998. Hence, the countries all over the world along with motor vehicle manufacturing and regulatory communities have developed dynamic side impact tests and evaluation criteria to reduce the severity of the impact of accidents. Correspondingly, the international research community has set test procedures for performing side-impact collision into poles. The purpose of this test is to minimize the effect of side-impact collision risking vehicle occupant [11].

Crash conditions must imitate the real crash scenario's that occur in the real-time environment. In this, the results are evaluated based on two approaches: the worst-case approach and probable condition approach. The Roadside safety community generally test the cars with the worst-case scenario approach and the test conditions with the speed of 50 km/hr [11].

For BEV, Euro NCAP (New Car Assessment Program) also conducted a 29 km/hr pole test for i-MiEV, the result indicated no harm caused to the battery pack, but the exterior battery pack was closer to the deformation which caused by the Vehicle body. With the increase in the speed of 50 km/hr, the Australian New Car Assessment Program (ANCAP) concluded more intrusion in the rear floor area compared with 29 km/hr impact. Hence, with the speed of 50 km/hr side-impact

pole results in severe damage to the occupant, potential danger to rescuers and other road users [12].

2.4.2 Side pole: Worst case scenario

During crash analysis, side pole load can act on any position of the sill beam. To narrow down the scope of research, concluded to focus in-between cross beams because that is the weakest position for an object to intrude and this intrusion might also lead to an explosion as shown in figure 2.9.

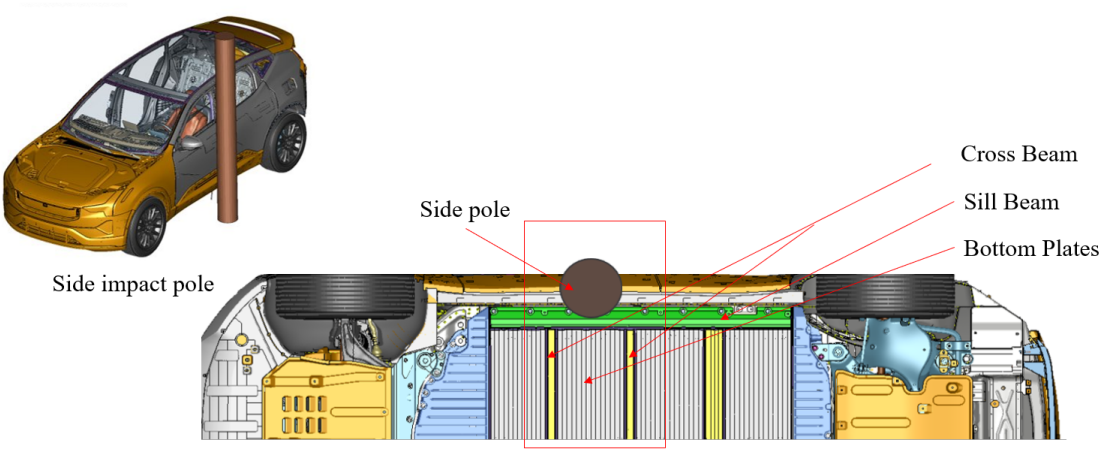

Figure 2.9: Bottom plate worst case scenario for side impact load case [6]

2.5 Structural optimization

Structural optimization is the best way to obtain a design solution for the battery housing structural problem when solving it through a systematic mathematical approach.[13] "In mathematics, 'best' is defined as a minimum (or maximum) of a battery housing structural problem" [14].

Structural design form

- Objective function (f): It describes the objective of the optimization which has to be minimized or maximized. Here, we have considered volume fraction, mass fraction, and compliance as a potential objective function [13].

- Design variable (x): It describes design which can be modified and here we have considered design space, member size, manufacturing constraints, displacement and material as a potential design variable [13].

- Parameter (p): It represents the response of the design and here we have considered stress, displacement, buckling, mass [13].

- The equation 2.2 shows the optimization problem in a mathematical way [13].

$$minimize f(x,p) \tag{2.1}$$

x
subjected to

$$g(x,p) \leq 0 \tag{2.2}$$

$$h(x,p) = 0 \tag{2.3}$$

f : function
p : parameters
x : design variable
g,h : constraints

There were various studies which followed optimization methodology to achieve weight reduction. Among various studies, the literature from a few articles has been discussed below.

The application of optimization methodology along with structural finite element analysis was followed to develop the robust and lightweight battery module frame [15]. A similar methodology was inspired by this report. The mass optimization of the hybrid battery pack was done using CAE simulation according to one technical paper [16]. The sizing was followed to determine ideal thickness for components and topology optimization was performed to find critical load paths for potential changes in design for mass reduction. Vehicle safety heavily depends on the safety of the battery pack which in turn is dependent on its mechanical features, such as the ability to resist deformation and vibration shocks. Also, a lighter weight vehicle is preferred because it can increase the range of vehicles and the life cycle of a battery pack. In this study, a design optimization methodology is proposed to optimize the features of mechanical design (e.g. minimization of mass, maximization of minimum natural frequency, and minimization of maximum deformation) of the battery pack enclosure [17].

2.5.1 Topology Optimization

Topology optimization is the mathematical method which optimizes the structural layout of the design space with the given load criteria, material, degree of freedom, constraints, and objective functions [13]. This optimization is limited only to linear static analysis for the simplification purpose, however, it can also solve non-linear static simulation. In detail study on design setup and optimisation result on Topology optimisation is given in section 7.3 .

2.5.2 Topography Optimization

Topography optimization is an advanced form of shape optimization which utilise sheet structure and changes it by adding stamped beads. In this way, stiffness is maximized without adding mass [13]. This approach is used for sheet metals only which has a thickness of 0.5 to 6mm. Here, mid-plane or shell mesh has to be assigned when solving through the Topography method in Altair HyperMesh software. In other words, the cross-section is an important parameter which is used as a design variable. Additional changes to the layout of the design model cannot be made, however stress concentration, displacement, compliance can be minimized by modifying the shape of the design model. In detail on design setup and optimisation result on Topography optimisation is given in section 7.4.

Various studies have followed the topography optimization method to increase the stiffness of structures. A few of them were discussed below.

The article on topography optimization of the stiffened square plate under uniform distribution pressure proves that the performance of stiffened square plate can be increased by approximately 80 % in terms of tension and compression using the topography optimization method [18]. This article also suggests potential designs of the stiffened square plate by performing topography optimization of finite element analysis. Another article on the topographical design of stiffeners for plates against blast loading [19] introduced two new structural configurations of stiffened plates which made optimal designs to improve the explosive-proof performance through distributing stiffener topology on the plate in comparison to the baseline design. These studies show the potential for the application of topography optimization methodology to minimize the weight and increasing stiffness with respect to loading on the structures.

2.6 Current trends in Industry

The aim of the investigation about trends in the industry is to gather more data about different approaches used by the researchers and companies in solving the problem. It also discusses the latest trending technologies, solutions, parameters from various journals, patent studies, websites, magazines, and books.

There are various articles, journals, and books which have interesting works on weight reduction techniques in different applications of industries.

The *Volkswagen led European super light car* adopted a multi-material approach to reduce weight in a vehicle body structure and a reduced weight of 85 kg. A body structure with different materials based on the criteria such as cost, density, quality, energy absorption, structural integrity, stiffness, form-ability is selected. Final weight and material distribution are generated from the computerized simulations. For the body structure weight, 53 % of material is contributed, following up with hot-formed steel 36% and magnesium about 7 % overall weight [20].

General Motors and Chevrolet have experimented with *Heat activated smart materials* to eliminate mechanisms. To open the rear hatch vent some mechanism is needed. However, the shape memory alloy wire has a different approach, wherein they contract when it is energized by electric current or hot air, which activates the mechanism to open the vent. The wire returns to the original position when the electric current or hot air is ceased. This saves 1.1 pounds of total weight as compared to heavier motors [20].

Aluminum is weight-saving material that can be used in components such as trunk lids and door inners. However, manufacturing processes for aluminium to form complex shapes are quite limited. *General Motors* solved this issue by collaborating with the company VTP and Kaiser Aluminum to develop a Quick Plastic forming (QFP) process which can ease the complex shapes. In the QFP process, heated aluminium material in an airtight seal blown against the die to form the required shape. As a result, replacing steel with aluminium has resulted in 35 % weight reduction[20].

Extensive research is conducted by the OEMs to bring carbon fibers into the market because it has less density. However, they are challenged with the manufacturing cost which contributes to 80 % of the total cost of carbon fiber. The Oak Ridge National Laboratory (ORNL) is trying to bring down the cost to 130 SEK/kg. According to the research lab, advanced surface treatment, plasma oxidation, and microwave-assisted plasma carbonization are the key technologies to reduce the weight of the carbon fiber [20]. Industries such as Helicopter manufacturing prefers metals over Composite materials because composite material cannot take up the large strain without fracture. However, composite materials are having a higher potential to absorb a large amount of load when compared to ductile materials such as aluminium [21].

By investigating different weight reduction techniques, the investigation about the current trends in the industry served as a good foundation of knowledge for the development process in the thesis work.

3
Methodology

This chapter explains different methods and tools followed in the several stages of thesis work.

The structured approach to solving the problem has been followed as it eliminates uncertainty and will lead to innovative solutions. Also, this approach enhances productivity and encloses all the solutions [22]. The project approach is shown in figure 3.1.

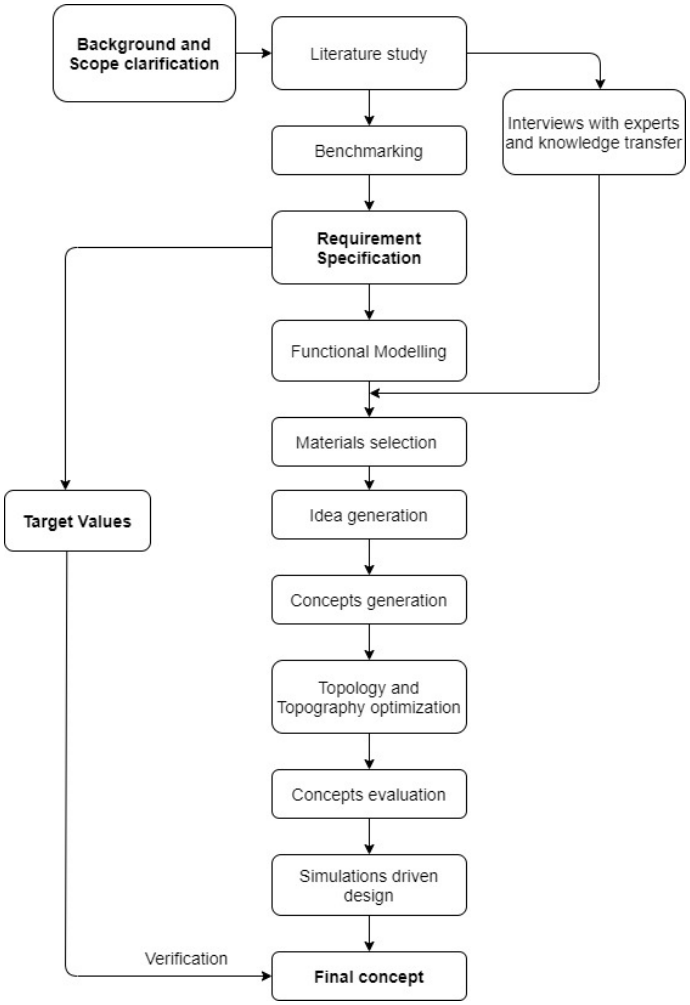

Figure 3.1: Project Approach [22]

3.1 Literature study

The literature study was carried out based on the research questions framed for the thesis work. Initially, the study was carried out with a wide scope of search on the battery pack involving battery tray, cover lid, cooling system, modules, bus bars, battery disconnect unit, and high voltage electronics. Later the study was gradually narrowed to the components in the battery tray carrier such as bottom plates, crossbeams, castings, and extrusions. The methods used in the literature search were journal search and Volvo intranet portal search. For the broader exploration of the study, inspiration for the ideas was taken from different industries as the pattern tends to repeat across the different industries. The scientific effects of the different problem solutions add value often in determining creative solutions.

The literature study also aimed at the existing research on the usage of topology optimization and topography optimization methods in the area of the battery housing.

3.2 Technological assessment

The technological assessment of battery housing was performed involving methods such as data collection from interviews and knowledge transfer sessions, competitive product benchmarking and SWOT analysis of existing battery housing of Volvo Cars.

3.2.1 Interview guide and Knowledge transfer sessions

The interviews and knowledge transfer sessions were used as a way to collect the different perspectives of solving a problem. The interviews were conducted in a semi-structured manner with a structured agenda but freedom was given to the interviewees to share their thoughts and experiences flexibly. They also helped in gathering data to fill in the knowledge gaps during the data collection phase, assist with relevant materials and contacts and share trending knowledge. These interviews and knowledge transfer sessions were necessary to oversee the problem from a different angle, and based on the interviewee past work experience.

3.2.2 Competitors benchmarking

Initially, the competitor BEV models were identified and compared based on battery pack energy densities, range of vehicles, and battery housing weights. The benchmarking data has been gathered and analyzed with the help of using competitive maps. The competitive maps helped in the visualization of comparison between competitors. Finally, the opportunities for improvement for the development of battery housing were identified from the benchmarking.

3.2.3 SWOT analysis

The SWOT analysis investigated the strengths and weaknesses of the existing battery housing, identified the opportunities for further development and external threats. The SWOT analysis helped in the evaluation of current battery housing before the start of the development of a new concept.

3.3 Functional analysis

The functional decomposition of the battery housing system was performed by using methods such as the black-box model, process flow model and functions mean tree. The main function was identified and broke down into sub-functions which helped in generating alternative ideas using the morphological matrix for idea generation.

The black box model helped in the identification of inputs to and outputs from battery housing to the surrounding environment. The process flow model identified many sub-functions within battery housing which helped in the functional breakdown of complex function. The functions mean tree identified several sub-functions along with associated means for each sub-function. This helped in the idea generation process.

3.4 Material study

3.4.1 Materials benchmarking

The materials benchmarking was performed by collecting the information of materials from interviews, knowledge transfer sessions, literature study, and CES Edupack. The materials benchmarking was conducted to investigate the material choices of competitors which helped in the decision making of material selection for concepts in the concept generation phase.

3.4.2 Materials selection

The benchmarked material information has been analyzed and compared based on strength to weight ratio, material cost, and sustainability which is the percentage of CO_2 emission. The potential materials were then selected for design and simulation of concepts. The materials used in the existing SPA2 battery housing were taken as a reference during the selection of materials.

3.5 Idea generation

The idea generation was performed to collect and generate different ideas to generate a new concept for the battery housing. The methods such as team brainstorming,

Morphological matrix, TRIZ method helped in generating ideas that helped in generating the concepts for further development.

The team brainstorming activity was conducted in a group to learn different approaches to problem-solving for innovative ideas. The morphological matrix was constructed using functional analysis and different sub-solutions were generated for each sub-function which helped to generate several concepts. The TRIZ method helped to investigate problem-solving approaches in different industries to implement in the current problem.

3.6 Topology Optimization

Topology optimization was the method used for weight reduction for aluminum concepts generated in the concept generation phase. This method helped in generating inspired concept designs from optimization results. The detailed information is explained in section 2.5.1

3.7 Topography Optimization

Topography Optimization was the method used for maximizing stiffness without an increase in weight for steel concepts generated in the concept generation phase. This method helped in generating inspired concept designs from optimization results. The detailed information is explained in section 2.5.2

3.8 Concept evaluation

The concept evaluation was performed for a few concepts which have been selected from the concept generation phase for further development. The evaluation has been done based on simulation results. The simulation of concepts was conducted in Altair Hypermesh and parameters for evaluation have been considered as concept weight, material cost, and crash safety parameters. The Kesselring matrix was used to evaluate concepts based on parameters. The existing SPA2 battery housing concept was used as a reference to which several other concepts were compared. This evaluation process was used to select the final concept which aims to perform better in parameters in comparison to existing battery housing concept.

3.8.1 Non-linear static simulation setup

For the crash test which is the dynamic simulation is solved through LS-DYNA. In this thesis work, for simplification purposes we are focusing on non-linear static simulation, hence we are compared the simulation result of the final concept battery housing against the existing SPA2 concept. Non-linear static simulation is considered instead of linear static simulation because crash simulation takes place at a

higher load case, and material behaviour in the plastic state in this study is more important.

- For the simplification of the simulation, instead of the whole battery pack, only the section of the battery housing was considered as shown in the figure 3.2. Hence, we have Bottom plates joined together to the sill beam and two Crossbeams attached to the Bottom plate and Sill beam.
- The side pole crash load was normalized to static force assumed value of 250 kN which acts on the sill beam.
- Four battery module force of 300 N was acting vertically downwards on four points of the Bottom plates as shown in figure 3.3.
- Ends of the bottom plate and cross beams were fixed in three degrees of freedom i.e. in x, y, and z-direction as shown in figure 3.3.
- Sill beam holes were mounted to the chassis in x, and z-direction as shown in the figure 3.3.

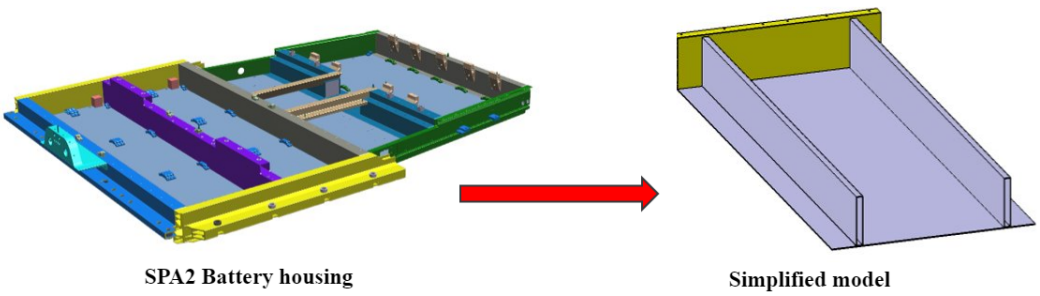

Figure 3.2: Battery housing section

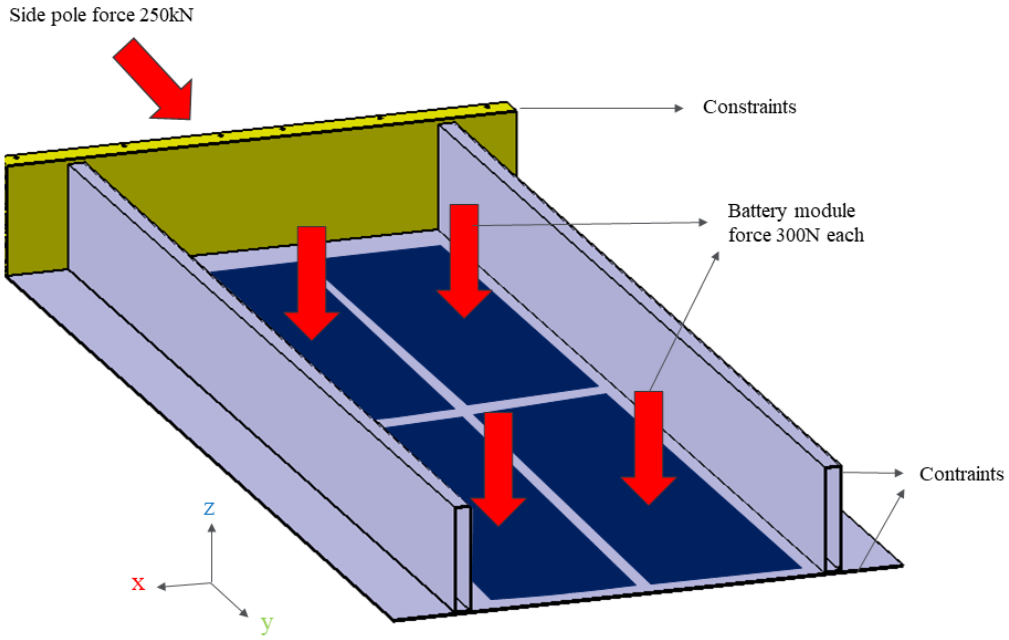

Figure 3.3: Simulation setup

3.9 Simulations driven designs

The simulations driven designs were conducted to develop the final concept into a fully functional model similar to the existing SPA2 battery housing concept. Several different designs were developed with inspiration from simulation results. Through this method, the designs were varied with different bead structures on the bottom plate by understanding the load path caused by static force on the sill beam.

Thus, all the methods followed in the thesis work helped to gain knowledge and guided in a structured way to obtain the results.

4

Technological assessment

This chapter on technological assessment involves data collection from interviews and knowledge transfer sessions, competitors benchmarking and SWOT analysis of battery housing to understand the opportunities for further development.

4.1 Data collection from Interviews and Knowledge transfer sessions

The interviews and knowledge transfer sessions were conducted to analyze the different perspectives on solving a problem. It helped in gathering data to fill in the knowledge gaps during the data collection phase, assist with relevant materials, and contacts and share trending knowledge. These interviews and knowledge transfer sessions were necessary to oversee the problem from a different angle, and based on the interviewee´s past work experience. Hence, we focused more on contacting people from different industries such as the ThyssenKrupp company, SmartBratt project team, Josephl project team, Chalmers solar team, and 9T labs along with CAE and safety experts at Volvo Cars.

The summarised insights of the interviews were shown in the appendix A. The decisions involved in the design, material selection, and concept development were taken from these insights of interviews as they helped to reduce the knowledge gaps.

4.2 Competitors benchmarking

- The objective of competitors benchmarking is to study the difference between the different BEV brands available in the market, and its strength, weakness, technological advancement, new business opportunities, gaps, quantitative data such as dimensions, weight, energy density, including material choices by comparing them against the existing SPA2 Volvo Cars battery housing.
- From this study, it assisted in focusing on the opportunity to improvise within the battery housing, understand the market, curtail the knowledge gaps, and backs up the reasons for the changes in the output. Besides, it also assisted in the concept development process in this thesis work.

- A2 Mac1 website [23] and Volvo internal reports [8] were the resources used to gather the data.
- Among various benchmarked competitors, Tesla Model 3, Chevrolet bolt EV, Jaguar I Pace, Audi E Tron model's battery packs were discussed below, as they were found interesting to inspire in this thesis work.

4.3 Tesla Model 3 benchmark

The Tesla Model 3 was released in 2018 for the USA market. It had the highest range of approximately 450 km compared to other car manufactures. The Model 3 battery pack weighs 460 kg and an energy density of 75 kWh. The unique feature of the Tesla Model 3 battery pack is cylindrical Panasonic cells which is one of the reasons for its lightweight, thermal efficiency, and high range. The top, bottom, and side views of the battery pack are shown in the below figure 4.1. The battery tray weighs only 53 kg. The interesting aspect of Tesla battery housing, unlike the Volvo cars, is that the battery tray is made of thick metal sheets of aluminum joined together and attached to two extrusions (aluminum 5000 series). The materials used for the battery tray is aluminum alloy. The cross beams in this battery housing are vertically built, unlike the Volvo cars battery housing in which they were horizontally built. One of the reasons could be the absence of front crash absorbing structures in Tesla Model 3 that made them build vertical cross beams in the battery tray. As the battery tray consists of reinforcements made of steel alloy, cataphoresis painting is used for corrosion resistance [8].

Figure 4.1: Tesla model 3 battery pack [8]

4.4 Chevrolet Bolt EV benchmark

The Chevrolet Bolt EV was released in 2017 for the North American market as shown in figure 4.2. The battery pack weighs 427 kg and has an energy density of 60 kW h. It consists of LG chem pouch cells. The battery tray weighs 66 kg and is made of steel alloy [23]. The battery tray made of steel alloy is an interesting idea that can increase crash performance and decrease material cost. This aspect is inspired for this thesis work. Also, corrosion resistance should have been addressed by Chevrolet as the battery tray was made of steel alloy.

Figure 4.2: Chevrolet bolt battery pack [23]

4.5 Jaguar I Pace benchmark

The Jaguar I pace was released in 2018 for the European market as shown in figure 4.3. The battery pack weighs 603 kg and has an energy density of 90 kW h. It consists of LG chem pouch cells. The battery tray weighs 75 kg and is made of aluminum alloy [23]. The interesting aspect about Jaguar I pace battery tray is its geometry in the front and rear which makes it beneficial in crash performance because that geometry can transfer forces equally into other arms of the battery tray.

Figure 4.3: Jaguar I pace battery pack [23]

4.6 Audi e Tron benchmark

The Audi E Tron was released in 2019 for the European market as shown in figure 4.4. The battery pack weighs 681 kg and has an energy density of 95 kWh. It consists of LG chem pouch cells. The battery tray weighs 99 kg and is made of aluminum alloy extrusion with aluminum sheet[23].

Figure 4.4: Audi E Tron battery pack [23]

4.7 Energy density comparison

Eight competitor BEV models have been considered for benchmarking. Their range of vehicles in km, individual weights of battery lid and battery tray carrier in kg, volumes of lid and tray in mm^3, Battery modules capacity in Ah, Battery voltage in V, and Battery Energy in kWh are compared. Battery cell manufacturers and geometries were studied for clear understanding. Along with these specifications, the materials used for battery lid and battery tray carrier were benchmarked. The benchmarking data was shown in the appendix B.1.

The metrics were carefully formulated for helping in comparison to competitors. To achieve the desired results, the considered metrics were individual dimensions, weights, and materials of battery tray and lid, Battery module energy, capacity, voltage, weight. The materials were further investigated by comparing with their physical, mechanical, and thermal properties. The comparable factor was decided to be kWh/kg for comparing all the competitors on an equal level. The comparable factor was calculated by the ratio of battery modules energy to battery housing weight.

The benchmarking data has been analyzed in the histograms for easy visual communication of parameters varying between the competitors in comparison with Volvo Cars. The comparable ratio used is energy density kWh/kg.

From figure 4.5 benchmarking visualization plot, Volvo cars SPA2 battery pack was seen to have the highest energy density compared to other competitors such as Tesla Model 3, etc. Tesla Model 3 battery pack has a high range (due to less weight and better aerodynamics) with less energy density and less cost of battery pack compared to Volvo Cars SPA2 battery pack. This creates a potential for the

cost reduction in the Volvo Cars SPA2 battery pack. Along with cost reduction, benchmarking analysis created a lot of potential areas for Volvo Cars SPA2 battery pack to develop.

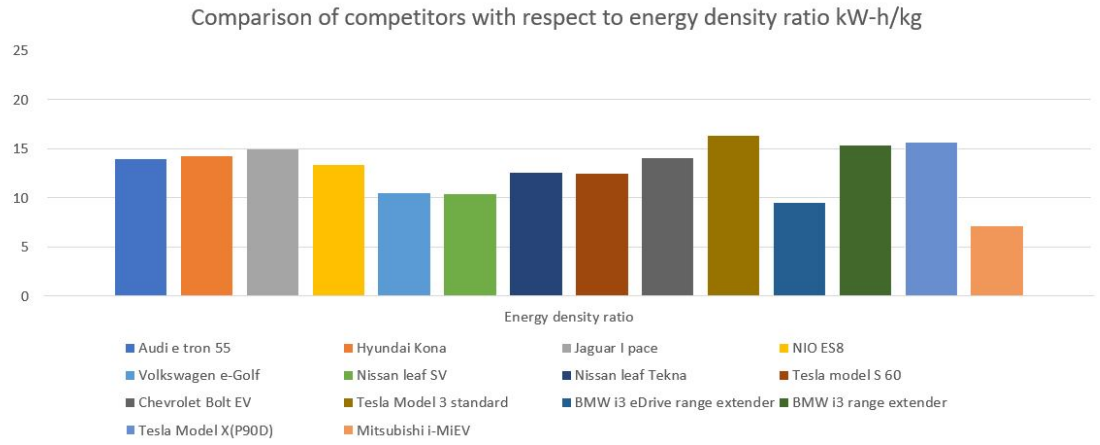

Figure 4.5: Benchmarking analysis visualization plot

4.8 SWOT Analysis for Battery Housing

The SPA2 Battery housing of Volvo Cars is looked into and SWOT analysis is performed by comparing various battery housings of different competitors as shown in the figure.

Strength

- Structural design of battery housing is compact, strong and safe according to Volvo standards

Weakness

- Structure is heavier due to Volvo safety standards
- Battery housing structure is expensive based on the material consumption evaluation
- Supplier limitations – material selection, manufacturing
- Too many components and manufacture problems to join them

Opportunities

- New Battery housing design
- Lightweight design
- Cost reduction
- New material choice
- Improvise manufacturing problems
- Smart integration of components

Threats

- Extensive use of Aluminum by many car industries might surge global price
- Battery carrier is heavier when compared to competitors like Tesla Model 3, Audi E Tron 55, Hyundai Kona.

This chapter helped to assess the technological maturity of development in the area of the battery housing and helped to identify the opportunities for further development of battery housing.

5

Requirements Specification and Functional Analysis

This chapter involves the generation of requirements specification and functional analysis using different methods namely black box model, process flow model, and functions means tree.

5.1 Requirements specification

This section involves requirements generation which is used during concept generation, evaluation, and verification of the final concept. The requirements specification was generated initially based on the information from data collection activities.

The requirements specification was formed based on the aim and objectives of the thesis work and also based on the Volvo cars requirement list. It was categorized into six rows: Size and geometry, material selection, Safety - Electrical, Mechanical and Thermal, Environment, and Supplier limitations. Each category has an objective that has a requirement such as demand or wish set by Volvo cars or thesis team or departmental team. This requirement has a target value or a statement, and verification was done by CAD modeling in CATIA V5, non-linear static simulation in Altair Hypermesh, and CES Edupack. The requirements specification is shown in appendix D.1.

5.2 Functional analysis

This section involves the identification of main and sub-functions for the battery housing, formulation of the black-box model, process flow model, and functions means tree.

5.2.1 Identification of Functions for Battery Housing

The battery housing is considered as a whole and its functions inside and outside interaction with the environment is identified in the following way.

- To enclose the battery modules
- To protect the battery modules

- To carry all the components of the battery system
- To withstand the external impacts
- To withstand internal pressure and internal generated heat
- To provide waterproofing, fireproofing
- To insulate electrical leakages, thermal leakages, electromagnetic current
- To be easily accessible for servicing
- To interact with the environment in a sustainable way
- To protect the users during crash situations
- To ease the user ergonomics
- To ease the manufacturing and assembling process

5.2.2 Black box model

The black box model is a framework used for the functional decomposition of a system. The battery housing is considered as a system and the inputs, outputs into and out of the system are considered [22]. The inputs into the battery housing are taken as a structural, electrical, and thermal type of loads because the primary function of the battery housing is to protect the components of the battery system from the external collision, an internal malfunction compromising the safety, and electromagnetic interference. As a final result, battery housing must safely protect all the components inside the battery housing and interact with the environment to keep the optimum working temperature inside the battery pack. Mounting components are also part of protecting the battery pack, but it is not focused on this thesis work, as it is considered as a complex system and out of scope. The black box model representation is shown in figure 5.1.

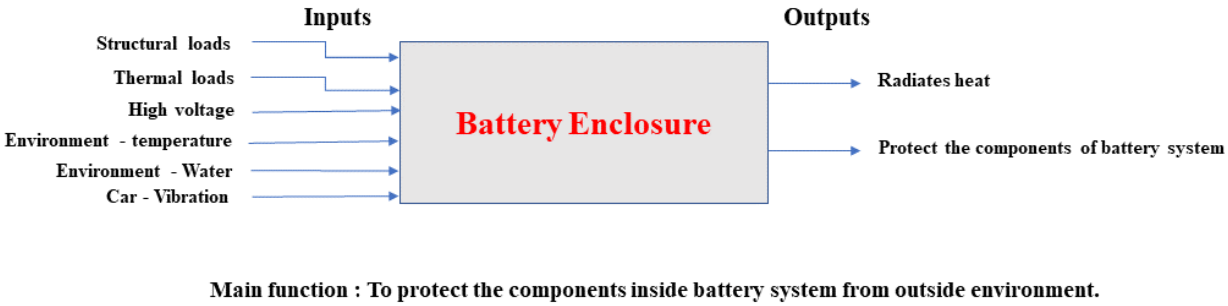

Figure 5.1: Black box model

5.2.3 Process Flow Model

In the process flow model, each function involved in the system is broken down into different sub-functions involved in the battery housing. Based on this sub-function, respective sub-solutions are determined [22]. To ease the functional breakdown of

the complex system, the process flow model is constructed to generate ideas from each sub-function in the battery housing or enclosure.

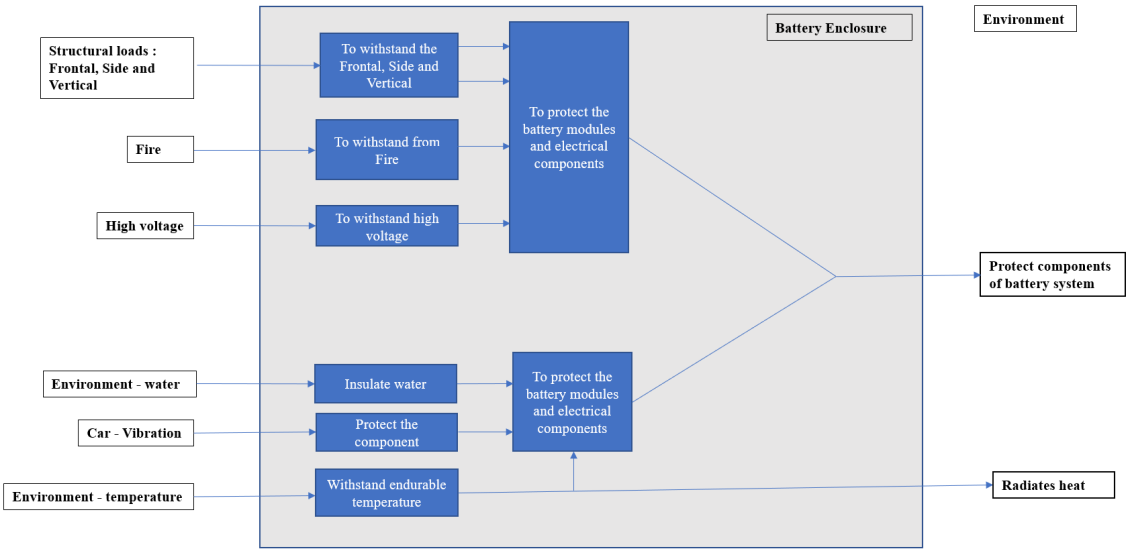

Figure 5.2: Process Flow model

The process flow model helped to identify the sub-functions of the battery enclosure whereas the black box model only helped to identify the inputs and outputs to the battery housing with respect to the surrounding environment.

5.2.4 Function means tree

The functions means tree is constructed from the main function of the battery housing. It is further divided into various sub-functions and different sub solutions are generated which helped in the creation of morphological matrix in the idea generation phase [22].

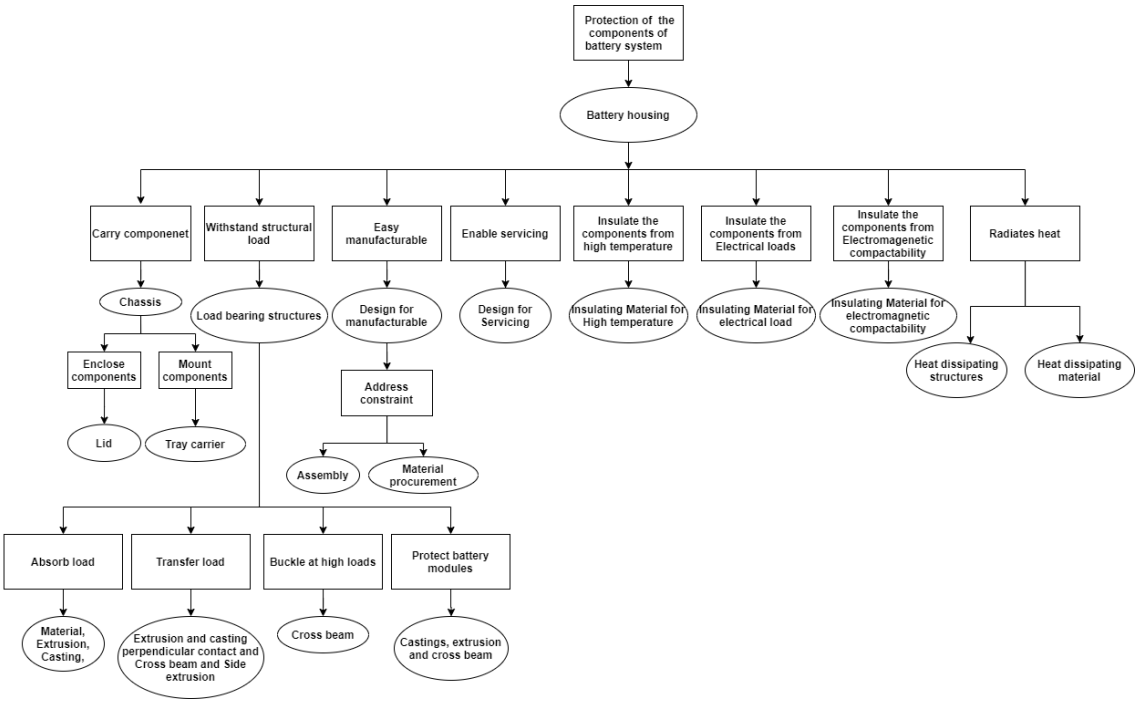

Figure 5.3: Function means tree

Thus the functional analysis helped in the idea generation phase of concept development to generate ideas from the obtained sub-functions in the functions means tree.

6

Material Study

This chapter involves the material study on bottom plates and cross beams and discussed the approaches followed for materials benchmarking, and materials selection. It also discusses in detail about physical and mechanical properties and environmental impact on material selection.

6.1 Materials benchmarking

Material data is gathered from various sources such as research institutes, ASM handbook, BEV benchmarking, and CES Edupack software. The first-hand material information gathered from interviews, literature study, and knowledge transfer sessions were benchmarked in an excel sheet to analyze the material choices for different components in battery housing used by different competitors. The materials used in existing battery housing were taken as reference and other materials were benchmarked in comparison to the existing materials which are shown in appendix C.

6.2 Materials selection

The scope of materials selection was to select a few potential materials feasible for the lightweight and strong design for crossbeams and bottom plates. The metrics used during the comparison and selection of the materials were specific strength and material cost. The materials used in the existing SPA2 bottom plates and cross beams were used as a reference in the comparison of materials. From this material selection, only thirteen materials were considered among the thirty materials as shown in figure 6.1. There was a set of three elimination process made to finalize the materials for the cross beam and the bottom plates.

In the first elimination process, seventeen materials were eliminated because of low strength to weight ratio (SWR), high material cost and based on a higher percentage of CO_2 emission when compared to reference materials (or existing SPA2 material choices).

In the second elimination process, based on the higher percentage of CO_2 emission following materials were eliminated - magnesium commercial purity ASTM 9980A,

magnesium mg 30 % B4C and aluminium 518 die-cast F which all have 44.2 %, 34 % and 14.7 % CO_2 emission.

Lastly, the third elimination process involved the dependency on the functions of the bottom plates and cross beams. For the bottom plate, material selection criteria were low-density material, low thermally conductivity, fire-proof, stiff, and have energy-absorbing capabilities. For the cross beams, the material selection criteria were high energy absorbing, stiff, and high carbon strength material because it does not prone to corrosion (as cross beams are sealed inside the battery housing).

In conclusion, the material chosen for cross beam and bottom plate were aluminium alloy A, and dual-phase steel YS600 cold rolled. The material properties are displayed in the table 6.1.

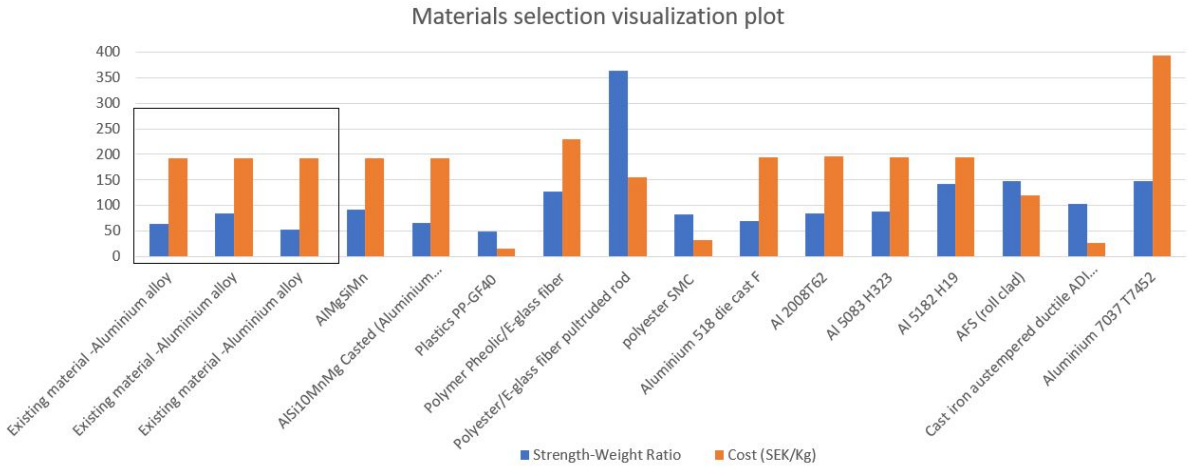

Figure 6.1: Materials selection plot

Table 6.1: Material properties

Properties	Aluminum alloy A	Dual phase Steel YS600 cold rolled
Density (kg/m^3)	2600	7800
Young´s Modulus (GPa)	72	200
Poisson's ratio	0.33	0.29
Yield strength (MPa)	140	600
Elongation (%)	13	15
Ultimate strength (MPa)	220	980
Cost per kg (SEK/kg)	22	7.15

6.3 Environmental aspect

Environmental sustainability is one of the driving factors in material selection for automotive components. This section describes the quantitative analysis of sustainability comparison of CO_2 emissions of aluminum vs steel in two stages: 1) Pre-manufacturing and 2) Post use or Recyclable. The study is limited only to these stages because these stages played a prominent role during the material selection phase. Hence the section describes the details of the economic and environmental performance of the vehicle in pre-manufacturing and post-use [24].

Pre-manufacturing or primary production

Generally, pre-manufacturing is the initial stage of the life cycle of the material where the material extraction takes place from the mining process. Here, from the earth crust virgin material is excavated and further processed to manufacturing phased to develop into a useful final product [25]. Hence, the production of virgin aluminum takes more energy than virgin steel, because of the high energy-intensive process. Being a similar manufacturing process for both the materials, the electricity required to operate the electricity varies for both the materials [24]. For pre-manufacturing, CO_2 emission for a steel is 2.4 kg equivalent per kg material and for aluminium it is 11 kg equivalent per kg material [26]. The pre-manufacturing cost for aluminum is 559.3 $ and for steel, it is 398.4 $ [24].

Post-use

This is secondary production where the material is recycled after its use. The steel or aluminum material collected for recycling can replace the virgin material with some losses. For post-use, CO_2 emission for a steel is 0.3 kg equivalent per kg material and for aluminium it is 0.4 kg equivalent per kg material [26].

Summarised findings on economic and environmental performance are shown in table 6.2

Table 6.2: Environmental aspect [26] [24]

Material	Aluminum	Steel
Pre-manufacturing (kg CO_2 -eq./kg)	11.0	2.4
Pre-manufacturing cost ($)	559.3	398.4
Post-use (kg CO_2 -eq./kg)	0.4	0.3

Thus material study helped in the selection of potential material choices for the concepts generated during the development phase.

7

Concept Development

This chapter discusses the methodology followed to develop bottom plates and cross beams concepts, topology concepts, and topography concepts. It also involves the evaluation of concepts against parameters and simulations driven designs.

7.1 Idea generation

The idea generation was carried out through different methods such as brainstorming, the TRIZ method, and the morphological matrix.

7.1.1 Brainstorming activity

The brainstorming activity was conducted within a group of 20 members at Volvo cars. The brainstorming activity aimed at identifying and understanding different approaches to problem-solving. Using the TRIZ method, various scenarios from different industries were provided to the audience for solving similar objectives of the thesis work such as weight reduction, material cost reduction, increasing safety aspect, and sustainability. Though several ideas were challenging to relate to the thesis work, the approach of problem-solving in achieving these objectives was inspired from the brainstorming activity into the thesis work.

7.1.2 TRIZ method

The TRIZ method is known as the theory of inventive problem-solving. The current problem in this thesis work can be solved by exploring similar areas in different industries other than the automotive industry. A similar pattern of TRIZ is implemented in the team brainstorming activity for generating solutions from team members and used for solving the current problem. The ideas from different industries such as adaptive multi-folding microstructures, hydraulics, energy absorption structures used in ship, crash barrier net, the landing gear of helicopter, pyrotechnically controllable adaptive system, etc were investigated and found to be interesting to address the current problem of the thesis work. These ideas can be used to implement in the sill beams of the battery pack to improve crash performance and they shall give rise to many dynamic concepts which were shown in the appendix E.0.2. The main constraint for bringing these ideas into reality is manufacturing feasibility due to which they were limited for further development.

7.1.3 Morphological matrix

The morphological matrix was constructed from the sub-functions which are derived from the functions means tree. The sub-functions namely "to withstand or absorb structural load", "to withstand electrical load", "to withstand thermal load", "to protect battery modules", "to protect electronic and electrical components" were listed in columns and alternative solutions for these sub-functions were listed in rows. This matrix helped in generating concepts based on merging several ideas from rows and columns. The morphological matrix is shown in the appendix E.1 to E.8. Many concepts were generated and visualized from this matrix were further explained in the next section.

7.2 Concepts generation

Several concepts generated from the morphological matrix were visualized in CAD models in CATIA V5. The concepts were developed on the bottom plate and cross beam components of the existing SPA2 battery housing. Among these, only a few concepts were selected for further development based on manufacturing feasibility.

7.2.1 Aluminium corrugated bottom plate

This bottom plate concept is made of aluminum alloy and has a corrugated cross-section to withstand vertical load in a better way than the flat bottom plate as shown in figure 7.1. To analyze the side impact force, we selected this concept for the simulation.

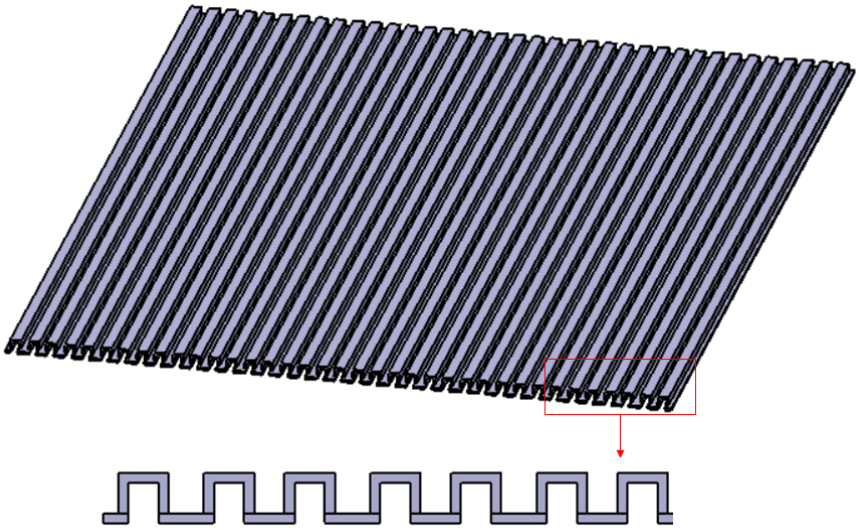

Figure 7.1: Aluminium corrugated bottom plate

7.2.2 Aluminium rectangular bottom plate concept

This bottom plate concept is composed of aluminum alloy and has rectangular holes along the length of the bottom plate as shown in figure 7.2. The cross-section has large holes and the main purpose is to reduce the weight. This concept has weight-reducing abilities, hence this was selected for the simulation.

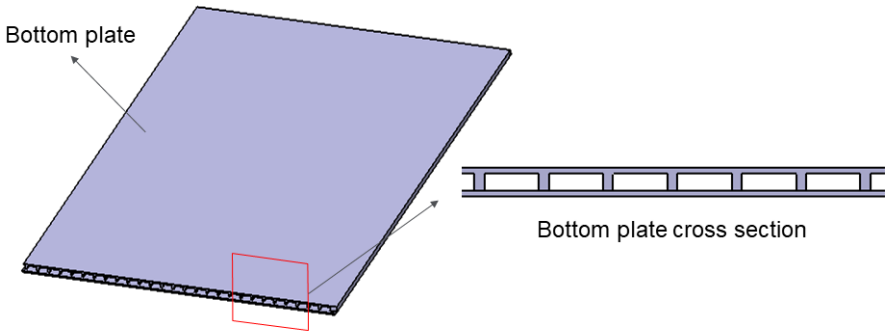

Figure 7.2: Aluminium rectangular bottom plate concept

7.2.3 Steel thin bottom plate concept

This bottom plate concept was made of steel alloy with a thin plate cross-section as shown in figure 7.3. This purpose was to introduce a steel plate and analyze the strength capabilities and improve its performance. This concept was cost-efficient than weight compared to all aluminium concepts. To verify the crash safety behavior, it was selected for simulation purposes.

Figure 7.3: Steel thin bottom plate concept

7.2.4 Steel corrugated bottom plate concept

This concept is similar to the aluminum corrugated bottom plate concept, but with the steel as a material and corrugated shape as the cross-section as shown in figure 7.4. Also, based on the literature study this concept can withstand more vertical load in a better way than the steel thin bottom plate. Since it is made of steel, it is denser in weight than aluminum. Hence, this concept was selected for simulation.

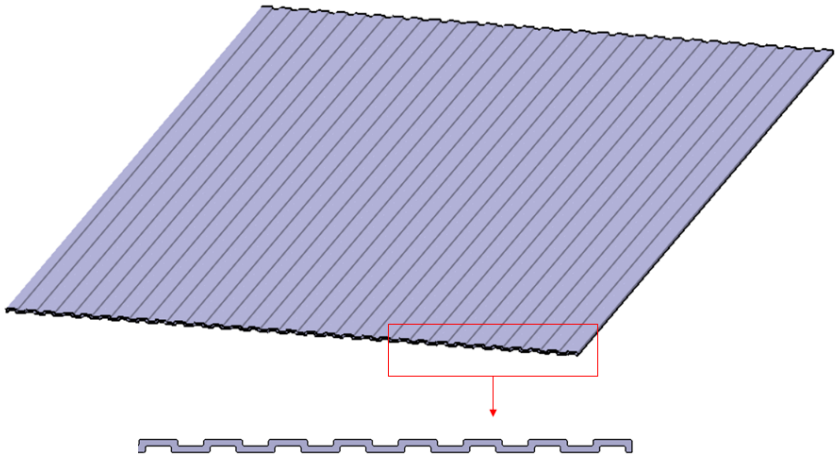

Figure 7.4: Steel corrugated bottom plate concept

7.2.5 T shape concept - Integrated cross beam and bottom plate

In T shape concept, both bottom plates and cross beams are integrated to form a single plate as shown in figure 7.5. This combination eases the manufacturing process, thus saving manufacturing cost and assembling time. To analyze the safety parameters, this was selected for the simulation purpose.

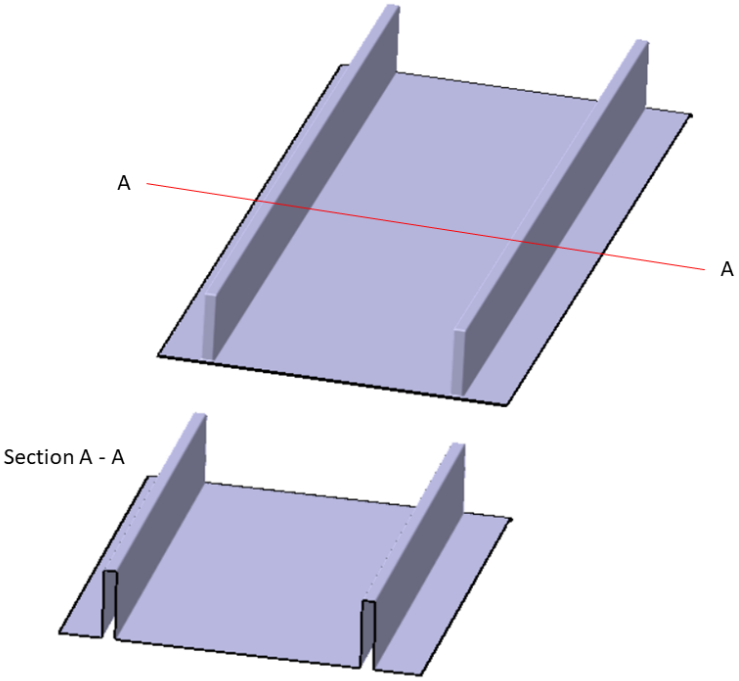

Figure 7.5: T shape concept - Integrated cross beam and bottom plate

7.2.6 I shape steel cross beam concept

I shape the cross beam concept is inspired from the TO section 7.6. This is composed of steel material and the top section of this concept has more material than the base surface because the load acting on the top surface is more. Also, this concept has manufacturing feasibility and one possible way to manufacture is by bending operation.

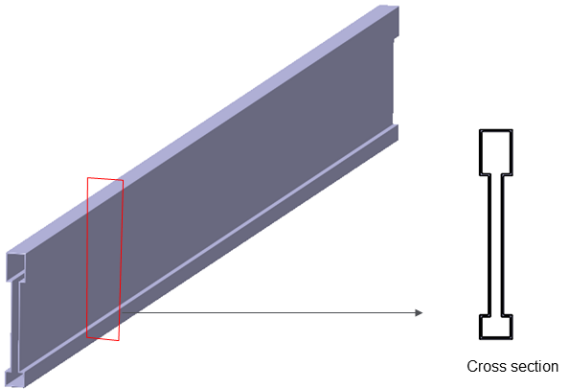

Figure 7.6: I shape cross beam concept

7.2.7 Rectangular shape cross beam concept

The rectangular cross beam is inspired by the existing cross beam and the design space available for the beam to mount. This has a great advantage in terms of manufacturing feasibility, because of its simple cross-section and one possible way to manufacture is by bending operation.

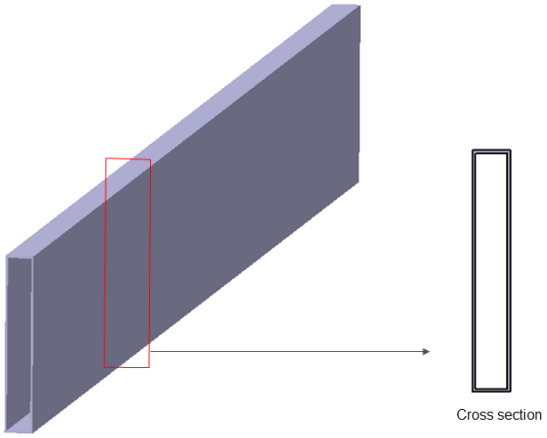

Figure 7.7: I shape cross beam concept

7.3 Topology optimization driven concept generation

In the topology optimization setup for solving aluminum cross beam and aluminum bottom plate, several simplification strategies were followed to gather more ideas, and solve quickly. Assigning natural and essential boundary condition for the topology optimization setup is similar to that of simulation setup as explained in the section 7.5.1 and optimization formulation such as objective, constraints, design and non-design space are discussed below. Many iterations with different objective have been solved to understand the correct optimization formulation and found promising one in the table 7.1 .

- Linear static simulation with 1/8th size of the battery pack is considered for quick computational result as shown in the figure 7.8 .
- Element type is volume tetra and size is 2 mm.
- **Design space creation** which is a solid CAD model that resembles that of the existing SPA2 battery housing. It helps in developing concepts through the topology optimization method. Here the model is subjected to loading conditions such as essential and natural boundary conditions, also, the model

is assigned with material properties and manufacturing criteria. As per the scope the thesis work, design space is cross beam and bottom plate, and non-design space is the sill beam as shown in the figure 7.8.

- **Non-design space** is the area where optimization is restricted. Hence, as per the design requirement, the non-design space for the cross beam is 10mm from the top and bottom surface, where on the top surface screws joins the lid and battery tray carrier and on the bottom surface it is attached to the bottom plate as shown in the figure 7.8. The sill beam is considered as non-design space because it is the non-focus area of the thesis work. Furthermore, topology optimization cannot be performed on it, as it is long slandered structure, instead, optimization can be achieved through size and shape optimization.

Table 7.1: Topology optimisation problem

Optimisation Formulation	Responses
Objective	Minimize compliance
Constraints	Volume fraction : 20% - 40%
	Stress : 180 MPa – 250 MPa
	Mfg. constraints : Extrusion in Y direction
Parameter	Element size : 2 mm
	Material : Aluminium

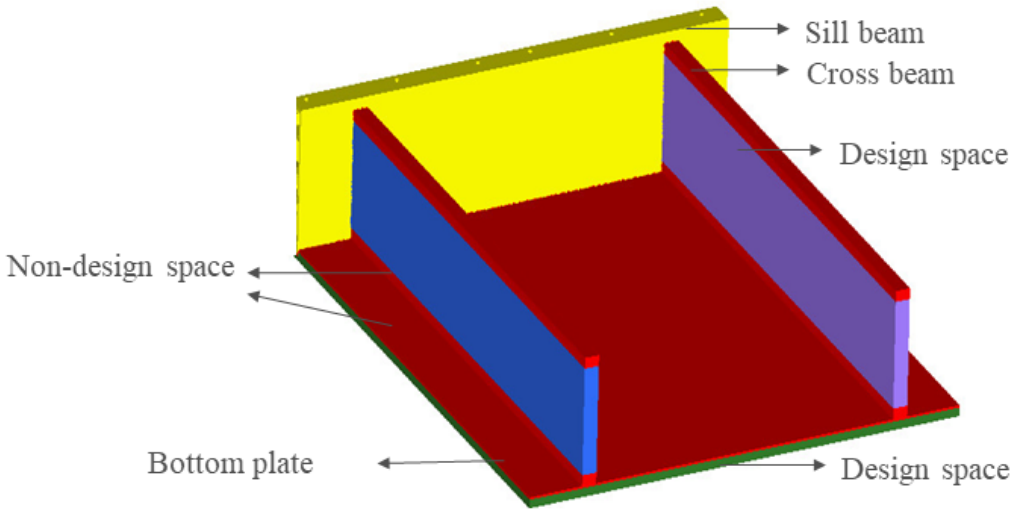

Figure 7.8: Battery housing design space

7.4 Topography optimization

To investigate steel concepts, the topography approach is followed because the thickness of the cross beams and the bottom plate is less than 2 mm. Topography optimization performed similar to topology, however, optimization response and mesh type vary which is described in table 7.2. The bottom plate and cross beam thicknesses are 1.8mm and 1.6mm.

Table 7.2: Topography optimisation problem

Optimisation Formulation	Responses
Objective	Minimize displacement in Y direction (intrusion region)
Parameters	Element type : PSHELL
	Element size : 4 mm
	Material : Steel
	Bead parameters
	Minimum width : 30 mm
	Draw angle : 60 degree
	Draw height : 15 mm

7.5 Concepts evaluation

Various concepts were generated through brainstorming, morphological matrix, topology and topography optimization. Among many concepts, only a few concepts were selected for evaluation as they were chosen for further development. Other concepts were limited for simulation as they were not manufacturing feasible and challenging to simulate with the decided setup. The evaluation of concepts was done by simulating in Hypermesh software with Optistruct solver.

The parameters established for evaluation of concepts were concept weight, material cost, manufacturing feasibility, and crash safety parameters such as intrusion (displacement in the y-direction) when acted upon crash load case and displacement in z-direction due to the self-weight of battery modules on the bottom plates. All the concepts were evaluated against parameters in comparison to the existing SPA2 concept in the Kesselring matrix. As mentioned in the section 3.3, all the concepts of battery housing were simplified for simulation purposes. Initially, the simulation of existing SPA2 battery housing was performed to evaluate the generated concepts against the baseline concept.

7.5.1 Simulation of existing SPA2 reference model

The simplified model of existing SPA2 battery housing was shown in section 3.3 where all the forces and constraints were represented. The non-linear static sim-

ulation was performed in which linear buckling analysis was also included. The material chosen for the simulation of the existing model was aluminium alloy A.

The post-processed results from simulation were displacement in y and z-direction, and von mises stress values. Displacement in y-direction was used to determine the intrusion due to crash load and displacement in z-direction which was used to understand the effect of battery modules self-weight on the bottom plate. The simulation results of the existing SPA2 concept were not revealed due to confidentiality. The maximum intrusion and bending on the bottom plate was found out to be 1mm and 0.5mm, and the maximum von mises stress value was found out to be 243 MPa.

A similar simulation set-up was used in performing the simulation of concepts. The concepts selected for simulation were listed below.

- Aluminium corrugated bottom plate concept
- Aluminium rectangular holes bottom plate concept
- Steel corrugated bottom plate concept
- Steel thin bottom plate concept
- Steel T shape cross beam and bottom plate concept
- Topology optimization driven concept
- Topography optimization driven concept

7.5.2 Simulation of Aluminium corrugated bottom plate concept

The Aluminium corrugated bottom plate was assembled to the existing sill beam and cross beams as shown in the figure 7.9. The enlarged view of the corrugated bottom plate cross-section was shown on the right side of the image. The maximum displacement was found out to be 7.14 mm on the bottom plate and maximum stress was found out to be 178.7 MPa.

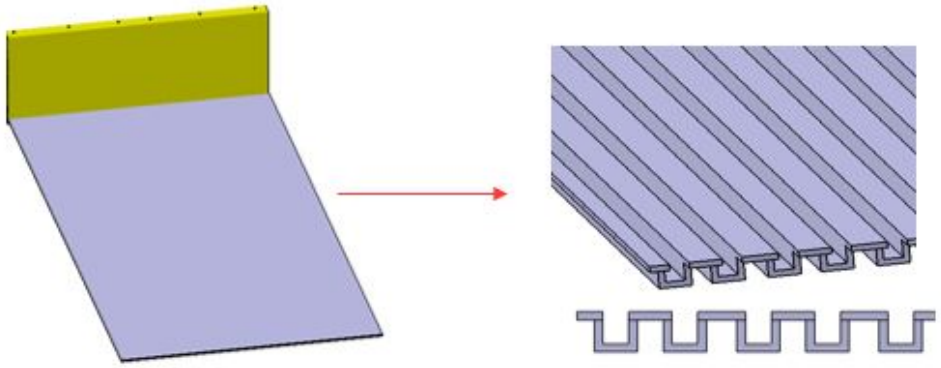

Figure 7.9: Aluminium corrugated bottom plate concept

From the results, the reason for high displacement in z-direction was that corrugated shape is better at withstanding vertical loads in comparison to the side loads on the sill beam which was considered in the simulation.

7.5.3 Simulation of Aluminium rectangular holes bottom plate concept

The Aluminium rectangular holes bottom plate was assembled to the existing sill beam and cross beams as shown in the figure 7.10. The enlarged view of the bottom plate cross-section was shown on the right side of the image. The maximum displacement was found out to be 13.6 mm on the bottom plate and maximum stress was found out to be 220 MPa.

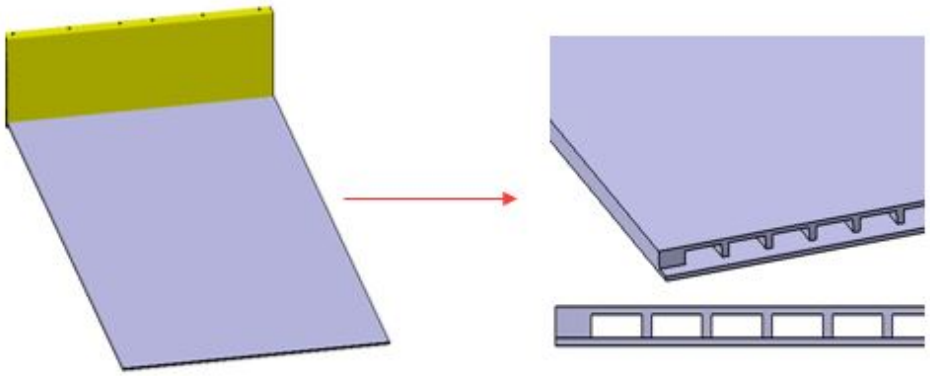

Figure 7.10: Aluminium rectangular holes bottom plate concept

From the results, the reason for high stress was that rectangular holes have sharp edges compared to elliptical holes in the reference model. The reason for high intrusion was that the concept has less weight with the same material.

7.5.4 Simulation of Steel corrugated bottom plate concept

The Steel corrugated bottom plate was assembled to the existing sill beam and cross beams as shown in figure 7.11. The enlarged view of the steel corrugated bottom plate cross-section was shown on the right side of the image. The maximum displacement was found out to be 2.8 mm on the bottom plate and the maximum stress was found out to be 366.2 MPa.

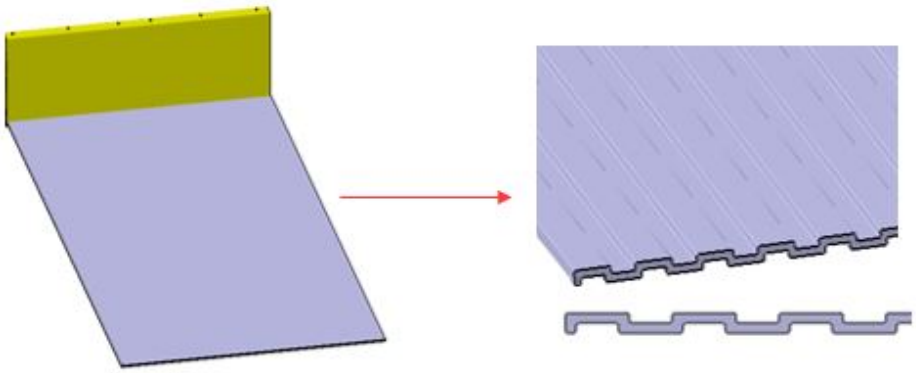

Figure 7.11: Steel corrugated bottom plate concept

7.5.5 Simulation of Steel thin bottom plate concept

The Steel thin bottom plate was assembled to the existing sill beam and cross beams as shown in figure 7.12. The maximum displacement was found out to be 4.5 mm on the bottom plate and maximum stress was found out to be 500 MPa.

From the results, the reason for more displacement in the z-direction is that the concept has less buckling mode factors compared to the existing SPA2 concept.

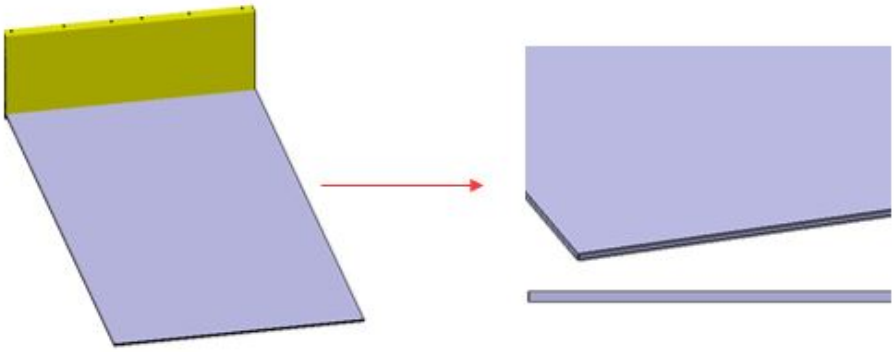

Figure 7.12: Steel thin bottom plate concept

7.5.6 Simulation of Steel T shape cross beam and bottom plate concept

The Steel T shape bottom plate and the crossbeam were assembled to the existing sill beam as shown in the figure 7.13. The maximum displacement was found out to

be 2.5 mm on the bottom plate and maximum stress was found out to be 600 Mpa.

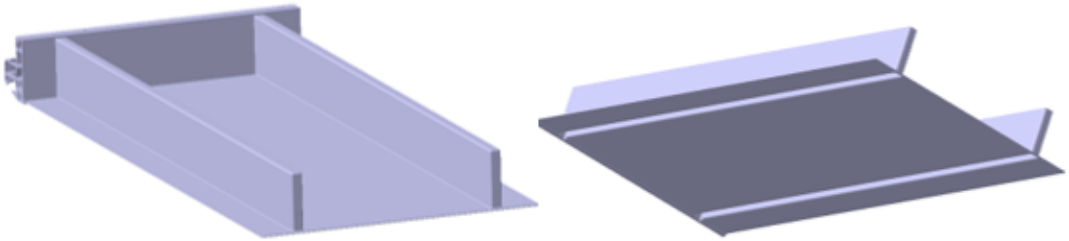

Figure 7.13: Steel T shape cross beam and bottom plate concept

7.6 Simulation of topology optimisation driven concept

Hyperview plots as shown in figure 7.14, recommended some area to remove material and some area to retain. However, there were some drawbacks when solving topology optimization, this study is based on the side pole acting on one direction if the side pole load acting directly on the cross beam contour plots changes instantaneously depending on the loading condition. Also, the lid was not part of the study which affected the outcome.

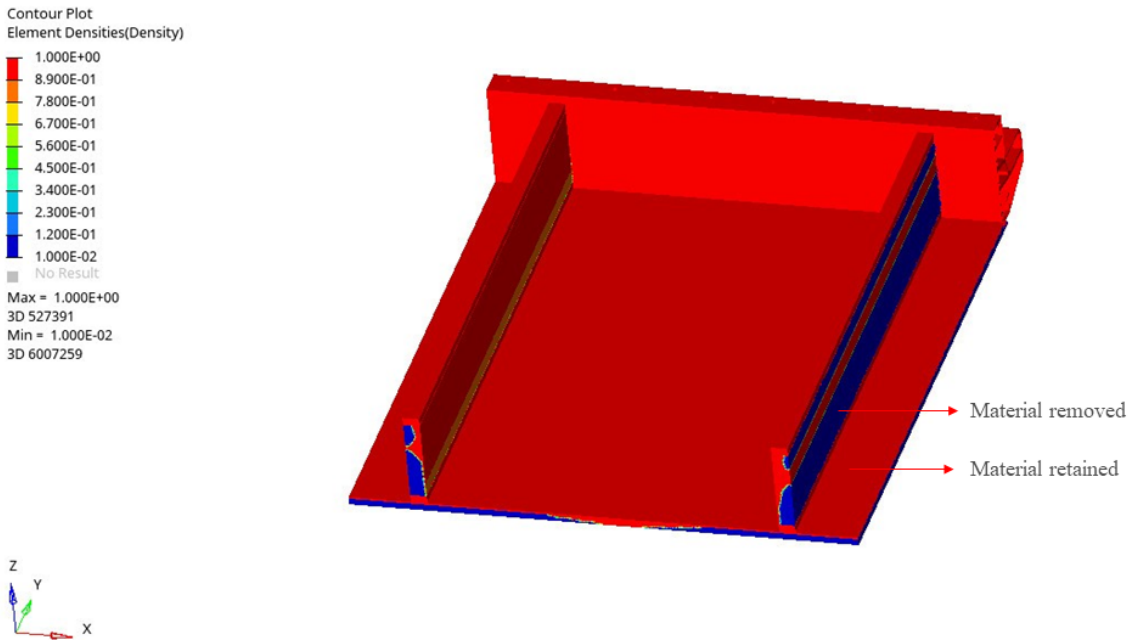

Figure 7.14: Topology optimisation results

7.7 Simulation of topography optimization driven concept

From the topography result, as shown in figure 7.15, it describes the shape changes of 15mm bead height in several areas of the bottom plot. The set target value for displacement in the y-direction is less than 1mm and the ultimate strength of steel is 990 MPa. The results for displacement in y-direction and stresses are 1.86 mm and 1060 MPa as shown in figure 7.16 and 7.17. These values are higher than the target value, however, by selecting the suitable boundary condition can further reduce the displacement and stress results.

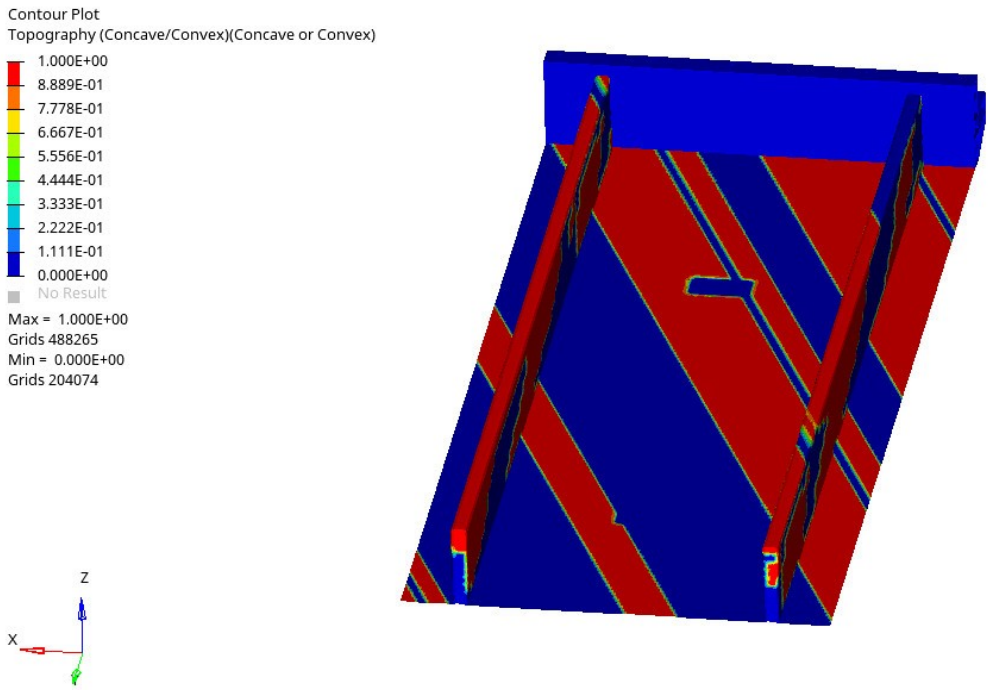

Figure 7.15: Topography optimisation results

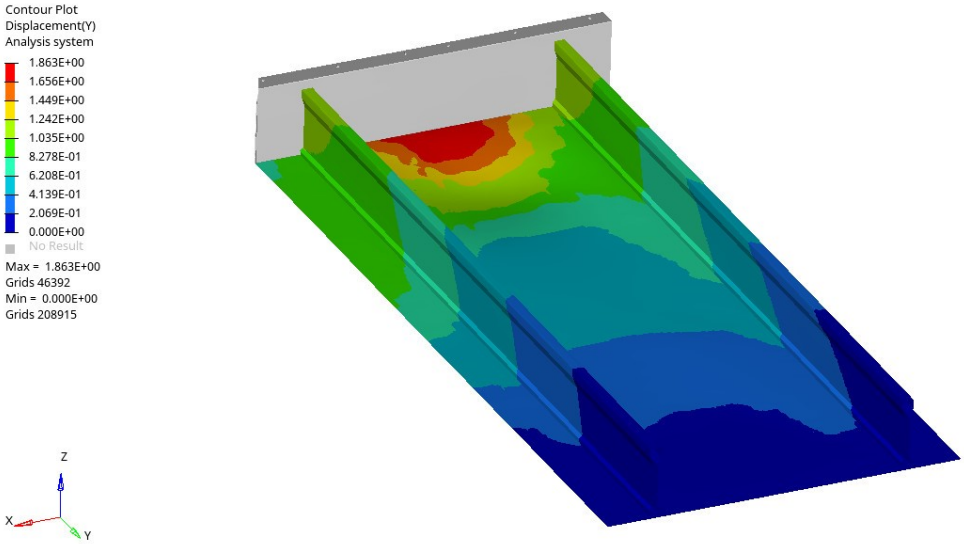

Figure 7.16: Topography displacement plot

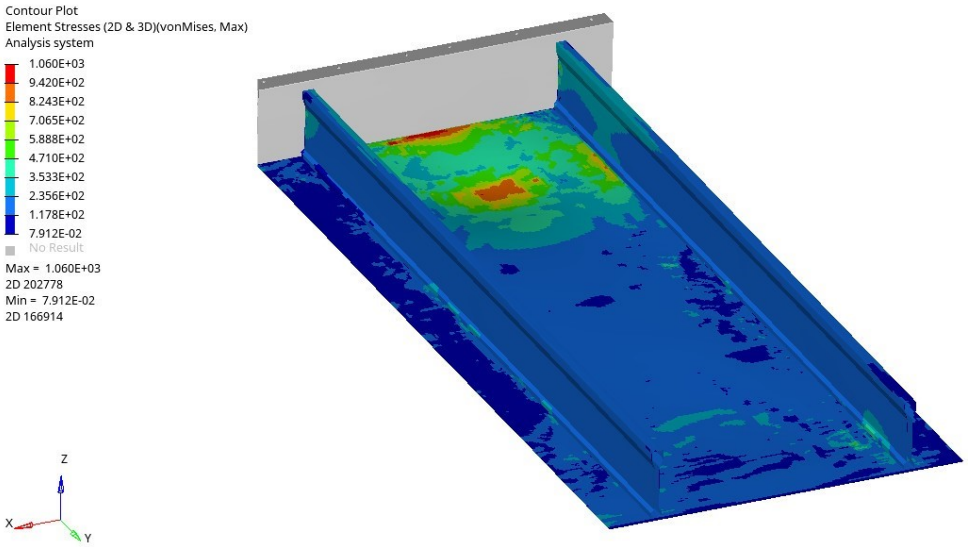

Figure 7.17: Topography stress plot

7.8 Kesselring matrix

The parameters chosen for the evaluation of concepts were weight, displacement in y and z-directions, and material cost. The parameters were arranged in order according to their priorities. The concepts were compared against the existing SPA2 concept in the figure 7.18. The ideal concept was expected to perform well at all the chosen parameters.

Concept	Weight of Concept	Intrusion : Displacement in Y (in mm)	Material Cost (SEK)	Bending: Displacement in Z direction (in mm)
Volvo Cars SPA2 concept (Bottom plate and Cross beam)	Reference	Target value:1 mm	450 SEK	Target value : 0.5 mm
Aluminum corrugated Bottom plate concept	8.44 kg	2.69 mm	185,68 SEK	7.11 mm
Steel corrugated Bottom plate concept	15.43 kg	1.57 mm	110.3 SEK	15.2mm
Aluminum Rectangular holes Bottom plate concept	10.85 kg	11.2 mm	238.7 SEK	0.27mm
Steel thin Bottom plate concept (2mm thickness)	10.26 kg	0.93 mm	73.3 SEK	6.15 mm
Steel T shape concept (2 mm thickness)	23.2 kg (Bottom plate and Cross beam)	1.01 mm	165.8 SEK (Bottom plate and Cross beam)	2.56 mm

Figure 7.18: Concepts evaluation matrix

On the whole, the concepts performed well against the existing concept in a few parameters and did not perform well on other parameters.

The concepts were compared initially based on weight parameters. The Steel corrugated bottom plate was limited for further development as it weighed more than the existing SPA2 concept.

Even though the aluminum rectangular holes bottom plate concept weighed less than the existing SPA2 concept, it performed worse at intrusion (displacement in the y-direction) parameter. So it was limited for further development.

The aluminum corrugated bottom plate concept weighed least than every other concept but it performed worse at buckling (displacement in the z-direction) parameter. So it was limited for further development as the ideal concept needs to perform well at all the parameters.

Among the remaining two concepts which were Steel thin bottom plate concept and T shape concept, the T shape concept appeared promising and seemed to have potential in terms of development compared to the existing SPA2 concept even though it did not perform better than Steel thin bottom plate concept. The main challenge observed with the T shape concept is manufacturing feasibility as it is difficult to deep draw it in the desired way.

The steel thin bottom plate concept which has a 2 mm thick bottom plate has been modified into a 1.6mm bottom plate to reduce weight in comparison to the existing concept and on other hand, beads structures were incorporated on to the bottom plate with inspiration from topography optimization method of increasing stiffness without increasing weight. The inspiration of beads on the bottom plate was also taken from the cover lid of the existing SPA2 battery housing.

7.9 Simulations driven design

The simulations driven designs were performed to develop the selected concept into a better concept which can perform similarly in parameters in comparison to the existing battery housing concept. The concept designs were varied based on inspiration from simulation results. The bead structures were varied on the bottom plate by understanding the load path from simulation results.

The main challenge is that there was a various loop of iterations involved to refine the concept. The topography optimization for steel concepts can reduce the CAD to CAE loops and accelerates the development process. The topography optimization has always been one of the methods for increasing the load-bearing capacity of structures that are sensitive to buckling in the car structures [27]. This process of simulations driven designs were done to develop into a better concept which can perform well in parameters similar to the existing concept. This transformation process from the selected concept to the final concept design will be explained in the next section 7.10.

7.10 Transformation into the final concept

For better understanding, the transformation from a steel thin bottom plate concept to the final concept is shown in the figure 7.19. Few important concept iterations were shown to understand the transformation of the bottom plate and cross beam concepts. The beads width, height, and the bottom plate thickness were considered as variants in these iterations to make the concept perform against parameters like intrusion and displacement in z-direction as similar to an existing concept.

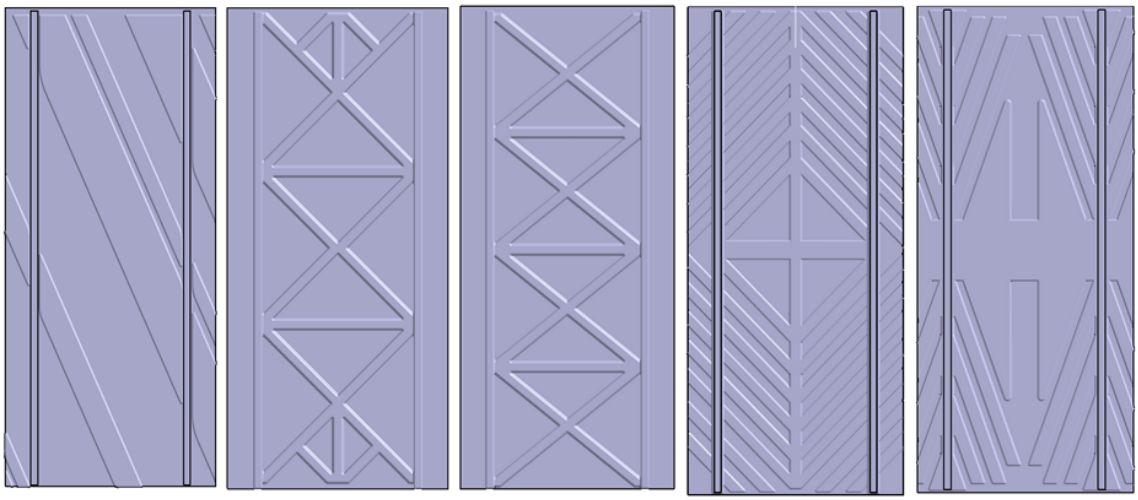

Fig.1. Topography inspired concept | Fig.2. Intrusion based design | Fig.3. Bending based design | Fig.4. Intrusion & bending design | Fig.5. Lid inspired concept

Figure 7.19: Transformation of selected concept into the final concept

Figure 7.19 explained the transformation of generated concepts through the simulations driven approach. Initially, the topography inspired concept is transformed into intrusion based design and bending based design based on simulation results and finally transformed into a design that is inspired by cover lid of the battery pack. This transformation of generated concepts based on the simulation driven approach led to the final concepts which will be explained in the next chapter 8.

8

Final concept

This chapter explains the final concept of the bottom plate and cross beam, and its evaluation with respect to the existing SPA2 concept. The final concept transformed through different designs from the topology optimization which was discussed in Chapter 7. It discusses the fulfillment of requirement specifications for the final concept.

8.1 Final concept description

The bottom plate final concept is a rectangular steel plate of L·W·H as A·B·Cmm with the thickness of 1.8mm and a bead height of 9.8mm to prevent the intrusion and take up the module weight without bending as shown in figure 8.1. The tree-like structures on the bottom plates are called beads. These bead ends were interconnected and take up the side impact load of 250 kN acting towards its direction as shown in figure 8.5. The bottom plate ends were attached to the sill beams and castings. The design inspiration for bottom plate was Topology optimisation and cover lid of battery housing. [Note: A·B·Cmm was written for confidentiality purpose].

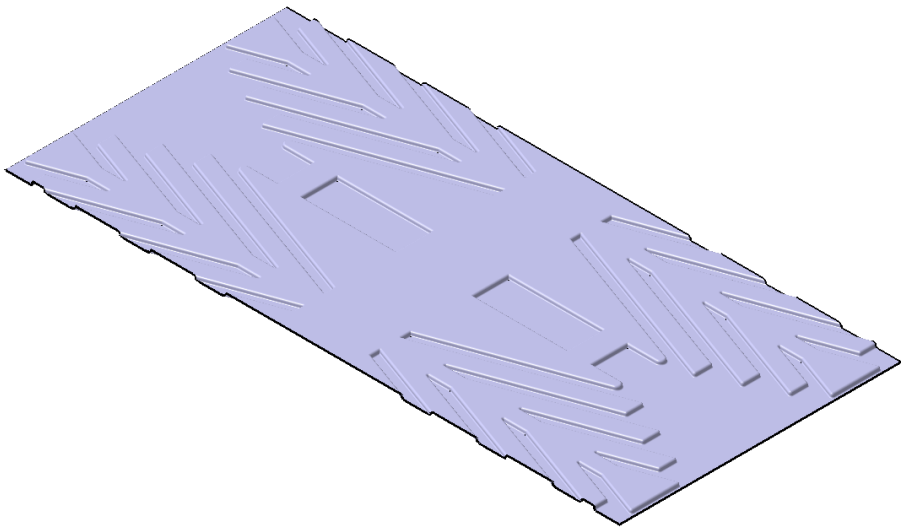

Figure 8.1: Bottom plate isometric view

The cross beam final concept is I shape a cross-sectional steel tube of the L·W·H is A·B·Cmm with thickness 1.6mm as shown in figure 8.2. It was mounted above the bottom plate beads as shown in figure 8.3 and ends were connected to sill beams. The design inspiration for the cross section was taken from topology optimisation.

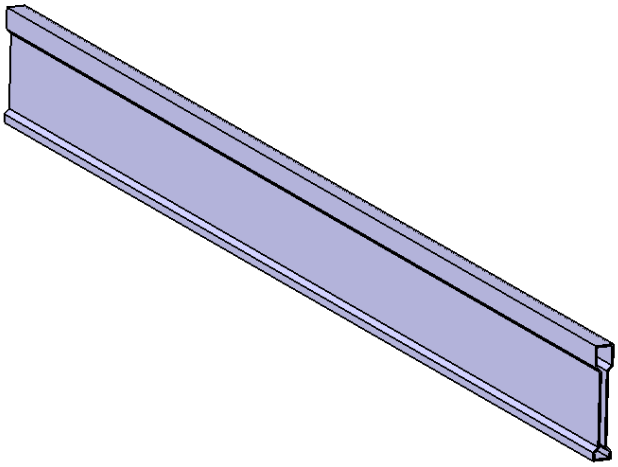

Figure 8.2: Cross beam isometric view

The sill beam, bottom plate and cross beams were assembled together to form the section of the battery housing. The figure 8.3 and 8.4 shows the isometric view and right side view.

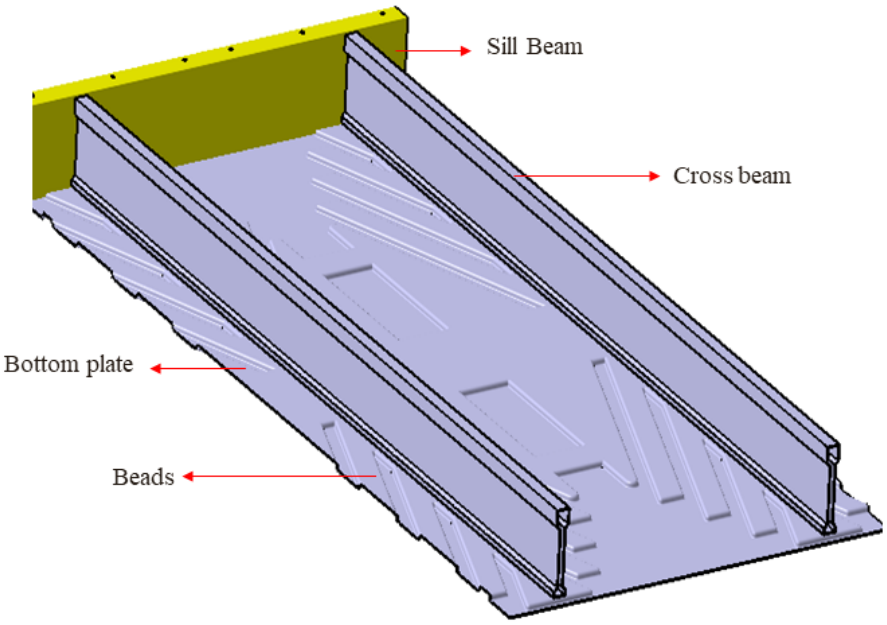

Figure 8.3: Final concept isometric view

Figure 8.4: Final concept right side view

8.1.1 Design for Intrusion

Design for Intrusion was done in the condition where the side pole crash load of 250 kN was acted on the bottom plate. The beads on the bottom plate must be able to restrict the load, which results in minimum displacement in y-direction. For the minimum intrusion, the following conclusions were drawn during iterative design process, when the load was acting in-between the cross beams.

- The beads were the tree-like structure which enhanced the stiffness or distributed the load throughout the plate.
- The bead pattern near the A region has to be eliminated, if not it acts as an obstruct and thus leads in high deformation during side pole as shown in the figure 8.5.
- The B region beads which have a bead width of 25mm reduced the intrusion because it acted as a path for traveling the intrusion load in the figure 8.5.
- The beads in the G regions can take up the load from the sill beam. The design purpose is to take 50% of the load from the sill beam and transfer across the bottom plate. This also acted as a platform for cross beam for mounting.
- The tree-like structure or beads have the unique potential to carry the load because it does not restrict the side pole load if restricted it deforms with the small loading criteria. Additionally, long beads with wider space allow the load to travel throughout the plate, and distribute it to the surrounding beads.

These were the conclusions drawn from simulation driven design iterations for intrusion.

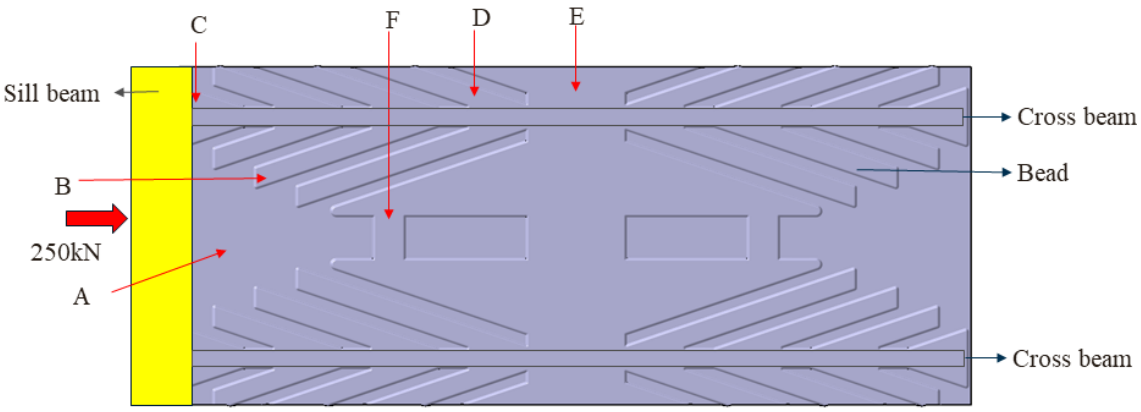

Figure 8.5: Bottom plate beads for minimum displacement in Y direction

8.1.2 Design for Bending

For bending, the four battery module weight of ´X´ N influenced the displacement in the z-direction. However, for the better design bending has to be minimum. These conclusions were drawn from the design iterations for a minimum displacement in z-direction.

- Horizontal beads such as C, D and E restricts the bending of all the beads which are connected to it as shown in the figure 8.5.
- The bead height and thickness of the plate influences the displacement in the z-direction. Hence for minimum displacement in the z-direction, bead height and thickness has to be increased. However, further increase in thickness leads to increase in weight and also further increase in bead height leads to exceed design constraint. For a good design, bead height and thickness have to be fine-tuned.

These are the conclusions drawn from simulation driven design iterations for bending.

8.2 Manufacturing Plan

The manufacturing process for the cross beam and bottom plates was the sheet metal forming process due to their low thickness values such as 1.6mm and 1.8mm. There are various sheet metal forming processes such as bending, extrusion, deep drawing, rolling, wire and bar drawing, shearing, and forging process. Sheet metal working process involved forming and machining operations performed on the metal plates or sheets, strips, and coils.

One possible way to manufacture the cross beams was through bending operations because different bending shapes can be generated by varying the bending pressure

and die shapes. Bending operation is a cold working process that is accomplished by using the equipment such as punch and die. The sheet is placed in between punch and die, punch moves in straight axis and die is stationary and when there is a relative motion between them, sheet metal deforms under plastic state and generates into the required shape. The following figure 8.8 shows the clear representation of bending operation along with sheet metal, punch, and die [28]. Another possibility to manufacture the cross beam was through extrusion operation, however, steel extrusions are limited because of the less ductility, shape complexity, and thickness of the cross-section. In addition, extruding profiles could be of higher grades of steel which are stiff and melt at the higher temperature, hence extruding die must be stronger than the extruding profile. Further development of a cross beam to integrate into the existing battery pack environment require machining operation.

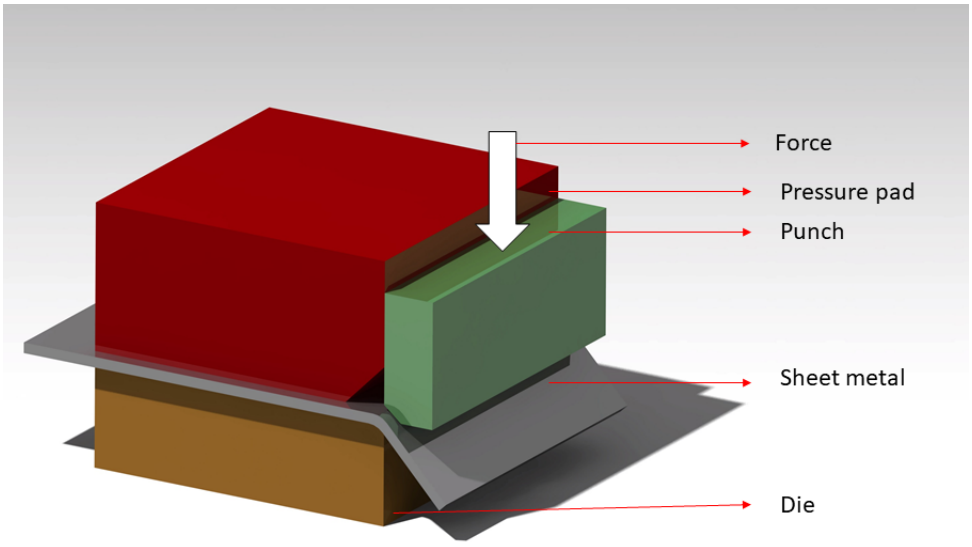

Figure 8.6: Manufacturing plan for cross beam [29]

One possible way to manufacture the Bottom plates was through deep-drawing operations. In this operation, flat sheet metals are deformed into cups or beads shapes by the mechanical action of the punch. A punch pushes the sheet metal into the required shape and a blank holder is used to clamp the blank on the die. The bead shape transformation takes place by stretching the sheet metal [28]. There are three Bottom Plates that could be merged into a single unit through the seam welding process.

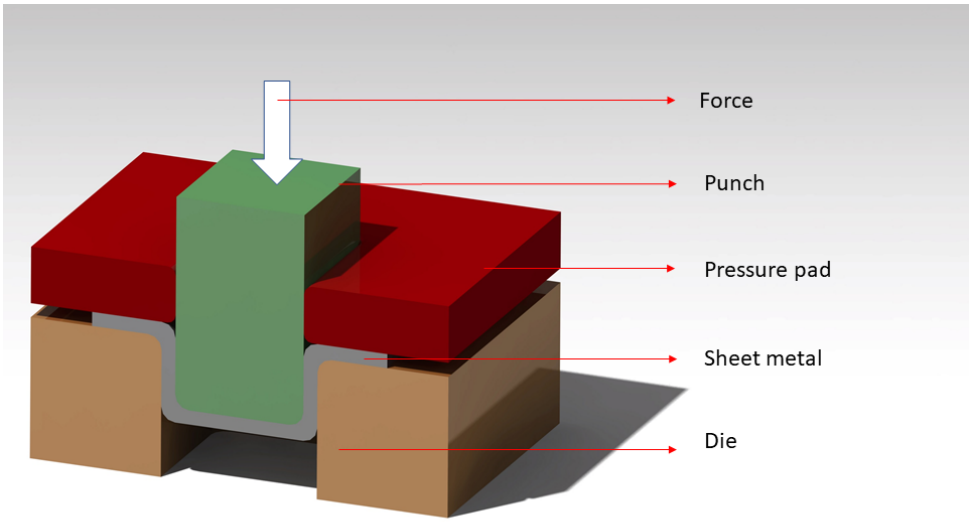

Figure 8.7: Manufacturing plan for bottom plate [29]

The bottom plates and cross beam could be assembled together through the seam welding process. This is a resistance welding process which utilizes electric current to lap join two objects and does not require filler material and no gas formed during the process [28].

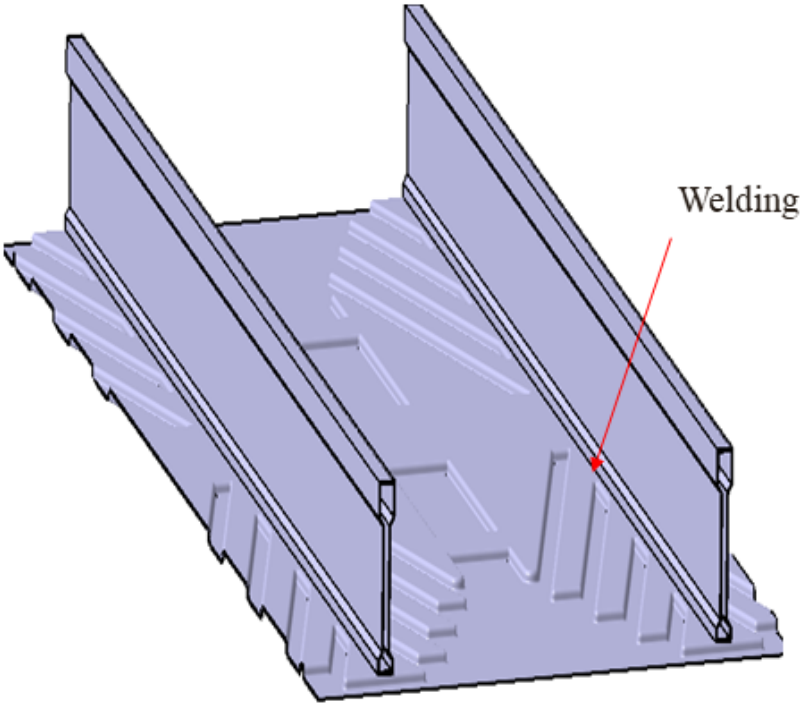

Figure 8.8: Manufacturing plan for bottom plate and cross beam assembly

8.3 Comparison : Existing vs. Final concept

8.3.1 Safety evaluation

The final concept was compared against the existing aluminum concept to precisely validate the results. The simulation set-up for both models was similar, except the existing SPA2 concept has three bottom plates composed of aluminium alloy joined or welded together, on the other hand, the final concept has a single bottom plate composed of steel. The intrusion, bending, and stress were the important parameters which was evaluated in this thesis work. However, in this thesis work simulation result for intrusion, bending and stress for existing SPA2 concept was not shown in this report work for confidentiality purpose, and rather discussed as target values.

- **Intrusion evaluation** : For the intrusion evaluation, minimum displacement in the y-direction due to side pole impact load acting on the bottom plate is measured. The target displacement value set is less than 1mm. The displacement result obtained in the y-direction was 1.28mm and the displacement pattern for the final concept was similar to that of the existing SPA2 concept, however, displacement was 28% slightly higher than that of the existing SPA2 concept. The resulted final concept has the potential to meet the requirements of Volvo standards which is shown in figure 8.9 below.

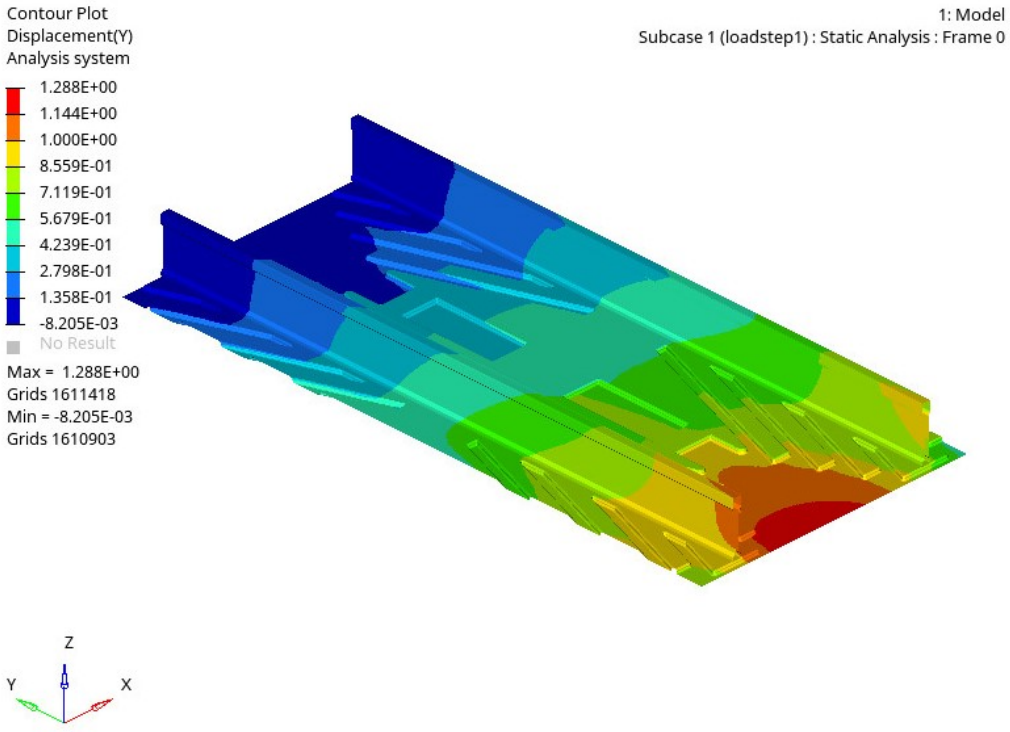

Figure 8.9: Intrusion result for the final concept

- **Bending evaluation** : For the bending evaluation, minimum displacement in z-direction due to module self-weight acting on the bottom plate was measured. The displacement target value set was less than 0.5mm. The obtained displacement result after performing simulation is 0.49mm in the Z direction and the displacement pattern of the final concept is similar to that of the existing SPA2 concept. The resulted final concept met the requirements of Volvo standards which are shown in figure 8.10.

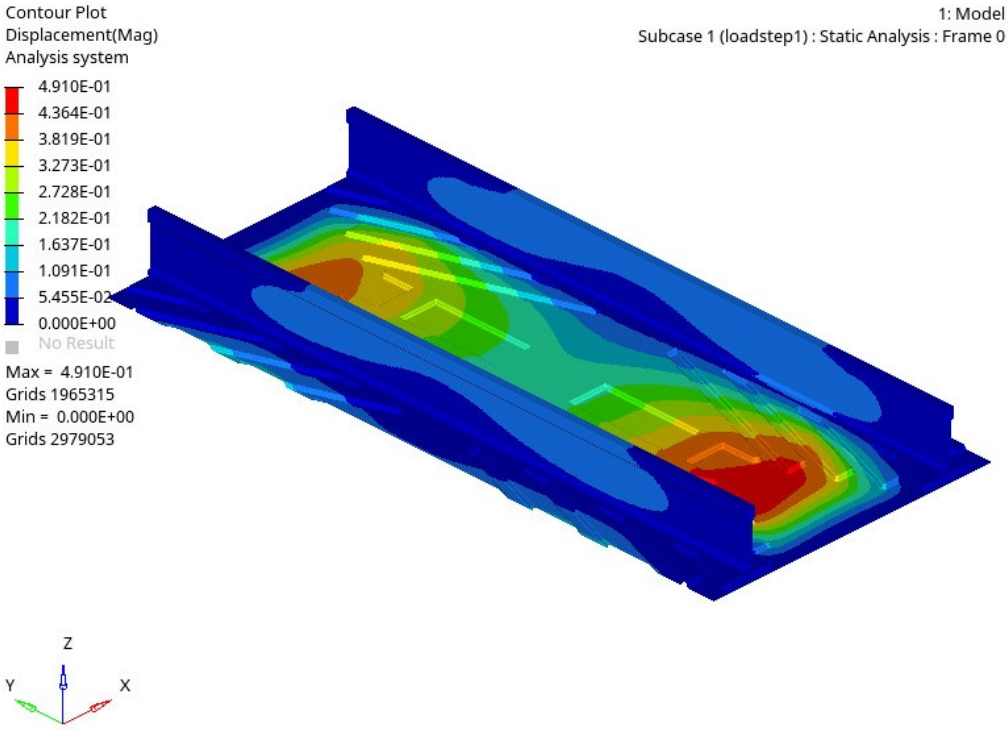

Figure 8.10: Bending result for the final concept

- **Stress evaluation**: For the stress evaluation, Von Mises stress was measured when acted by the side pole crash impact load on the bottom plate. For the safer design, stress must be within the ultimate strength. Here the ultimate strength was evaluated as the structure was subjected to crash load and deformation was evaluated in the plastic state. The maximum stress of the existing SPA 2 concept is 243 MPa and the ultimate strength of aluminium is 293 MPa. The maximum stress of the final concept is 606 MPa and the ultimate strength of Aluminium is 990 MPa. This evaluation clearly described that the design met the stress safety criteria.

  The resulted final concept has the potential to meet the requirements of Volvo standards which is shown in Fig 8.11 below.

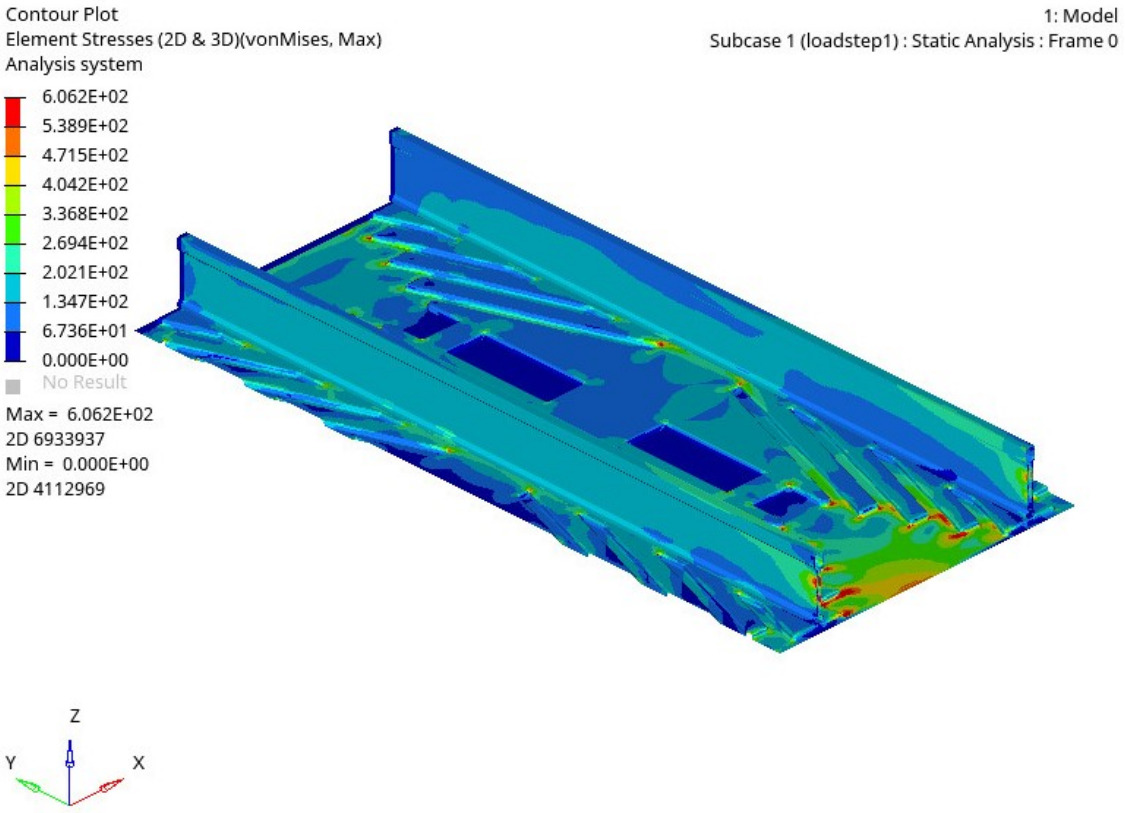

Figure 8.11: Stress result for the final concept

The summarised findings of intrusion, bending and stress evaluation are shown in the table 8.1

Table 8.1: Summarised findings : Safety parameters

Concept	**Final concept**
Materials	Steel – Dual phase cold rolled YS600
Target value: Intrusion (mm) **Resulted** : Intrusion (mm)	1 **1.28**
Target value : Bending (mm) **Resulted** : Bending (mm)	0.5 **0.49**
Ultimate strength of material (MPa) **Maximum Stress (MPa)**	990 **606**

8.3.2 Cost and weight analysis

The final concept resulted in increas of material cost reduction and increase in weight when compared to existing SPA2 concepts. The material cost per kilogram for steel

is around 7.15 SEK and for aluminium alloy is 22SEK. Considering the density of the final concept per section the material cost was calculated. The detailed information about cost and weight results in percentage was shown in the table 8.2

Table 8.2: Battery housing section : Cost and Weight analysis

Concept	**Final concept**
Material	Steel – Dual phase cold rolled YS600
Material cost reduction	**65.4%**
Total weight increase	**6.3%**

8.3.3 Machining and manufacturing lead time advantage

In the existing SPA2 concept, three bottom plates were joined together by welding. On the contrary, the final concept has a single bottom plate. Hence there is no need of welding which saves manufacturing lead time.

8.3.4 Material advantages

These were material advantages of the usage of steel in the final concept over usage of aluminum alloy in the existing battery housing concept.

- **Heat transfer advantage**: The car has to be suitable for both hot and cold climatic condition, hence heat transfer ability shall be minimum between the battery pack and environment, and the major contributing factor for heat transfer is the bottom plates. With the final concept as a solution, heat transfer was reduced to four times when compared with the existing SPA2 concept because thermal conductivity of steel is $42\,\frac{\mathrm{W}}{\mathrm{m°C}}$ whereas, aluminum thermal conductivity is $205\,\frac{\mathrm{W}}{\mathrm{m°C}}$. Hence, steel restricts environment temperature in a better way when compared to Aluminium.

- **Heat resistant advantage**: The final concept is twice better heat resistant than the Existing SPA2 concept because the melting temperature of steel is 1420 °C and aluminum is 630 °C.

- **Corrosion challenge**: Since steel material is used in the final concept which is more prone to corrosion than the existing SPA2 concept which is composed of aluminum material. Additionally, corrosion preventive measures such as metal coating needs to be taken care and one such metal coating process identified from benchmarking is electroplating.

8.3.5 Sustainability aspect

Steel as a material is more sustainable when compared to aluminium in the environmental aspect in terms of pre-manufacturing and recyclability . For the production of 1 kg of Steel, it is approximately 5 times lesser CO_2 emission when it is compared with Aluminium. For the recyclability of 1kg of steel, it is 0.1kg less CO_2 emission when it is compared with Aluminium.

8.4 Fulfillment of requirements specification for final concept

The final concept was designed against the established requirements specification. The verification of final concept performance against the established product-specific requirements was done and shown in the table 8.12.

	Product Specific Requirement	Target values	Set by	Verification	Status
1	**Cost**				
	R1 - Material cost	Less than the or equal to existing material cost	Volvo cars	CES Edupack	Verified
2	**Safety**				
	a) Mechanical				
	R2 - Intrusion	Displacement in Y direction less than 1mm	Volvo cars	Simulation	Refinable
	R3 - Bending	Displacement in Z direction less than 0.5mm	Volvo cars	Simulation	Verified
	R4 - Stress	Below the Ultimate strength of the material	Volvo cars	Simulation and CES	Verified
	b) Electrical				
	R5 - Electrical insulation (Resitant to electrical shocks)	Less than the or equal to existing material	Volvo cars	CES Edupack	Verified
	R6 - Electromagnetic compactability : Avoid the interactions from the surrounding electronics	Less than the or equal to existing material	Volvo cars	CES Edupack	Verified
	R7 - Electromagnetic Interference: Avoid the interactions to the surrounding electronics	Less than the or equal to existing material	Volvo cars	CES Edupack	Verified
	c) Material fuctionalities				
	D1 - Thermal conductivity	Less than 200 (W/m.°C)	Volvo cars	CES Edupack	Verified
	D2 - Melting point	More than 630 °C	Volvo cars	CES Edupack	Verified
	D3 - Corrosion resistant	withstand corrosion	Volvo cars	CES Edupack	Verified
	d) Thermal				
	R8 - Thermal Insulation	Able to withstand the fire release and fluid release	Volvo cars	CES Edupack	Verified
3	**Weight and Geometry**				
	R9 - Total weight	less than Akg	Volvo cars	Simualtion	Refinable
	R10 - Geometry -(LxWxH)	Equal to the Existing SPA2 concept	Volvo cars	CAD	Verified
4	**Manufacturability and assembly**				
	a) Manufacturable				
	R11 - Manufacturability	Design for Manufacturing	Thesis team	CAD design	Verified
	b) Assembly				
	D4 - Assembly constraints	Design for assembly	Volvo cars	Assembly	Verified
	D5 - Number of Components	Less component than Existing SPA2 concept	Thesis team	CAD design	Verified
5	**Environment**				
	D6 - Recyclable	More or equal to the Existing SPA 2 concept	Thesis team	CES Edupack	Verified
	D7 - Usage of sustainable materials	Less or equal CO2 emission than the Existing SPA2 concept	Volvo cars	CES Edupack	Verified

Figure 8.12: Requirement specification

9
Discussions and conclusions

This chapter involves discussion and reflection on studies performed in the thesis work. It also involves re-visiting the research questions and conclusions at the end.

9.1 Discussions

This section involves discussion and reflection on various sections such as benchmarking, material study, concept development, optimization methods and simulations.

9.1.1 Competitors benchmarking

The benchmarking data of competitors were gathered from the A2 mack1 website and Volvo Cars internal benchmarking reports. But there were knowledge gaps in gathering the benchmarking data of competitors such as the Tesla Model 3 battery pack. Due to the lack of information on the A2 mack1 website, the identification of material choices and construction of geometry in the Tesla Model 3 battery pack was challenging which influenced the comparison of Tesla Model 3 against Volvo Cars SPA2 battery pack. There is a scope for the identification of new potential areas of improvement of the Volvo Cars battery pack if that knowledge gap about the Tesla Model 3 battery pack was reduced.

9.1.2 Materials study

In the materials benchmarking, the information about the material properties of various materials was gathered. But the materials such as sandwich material, APM hybrid foams, hybrix, AFS were challenging to investigate due to lack of information on their material properties. In addition, the design and simulation of sandwich material was also challenging due to the limited knowledge.

In the sustainability aspect of the material study, the thesis work explored the ratio´s of mechanical and physical properties such as SWR, cost, and CO_2 emission during pre-manufacturing and post-usage. However, it would also be interesting to investigate the operational usage and manufacturing aspect of the material. The operational usage has a significant amount of impact on electricity because light weight contributes to the low energy [24].

In the chemical property study of material, this study limits the focus of chemical leakage from the battery modules affecting the structures of the battery housing components. However, dual-phase steel material is weak to acids and aluminum alloy A is good with acids [30].

9.1.3 Concept development

During the concept generation phase, various generated concepts were innovative but they were not feasible to manufacture by traditional methods. The lack of Design for Manufacturing (DFM) knowledge influenced the outcome of concept generation. Various concepts were limited for development due to lack of manufacturing feasibility which would have influenced the outcome of the final concept.

During the concept evaluation phase, there were challenges in the selection of concepts for further development. The evaluation of concepts was done against parameters such as weight, material cost, and safety parameters. Balancing the weight and crash safety parameters in the evaluation of concepts was challenging and the ranking of parameters was performed to tackle this challenge.

9.1.4 Optimization methods

Depending on the type of optimization problem setup, knowledge of topology and topography method is essential. Instead of the simulations driven approach, the best possible approach would be the application of optimization methods which shall consider all the parameters in a single simulation and gives the solution. Additionally, setting up the right boundary conditions, design and non-design space, constraints, and other parameters play an important factor. However, in some scenarios where the design freedom is completely restricted in-terms of constraints then it is difficult for a solver to give an optimization solution.

This thesis work explored the possibility of application of optimization methods and gain few design inspirations from it. However, it was challenging to take complete advantage of such methods due to the time constraint, limited resources, knowledge gaps, and boundary conditions.

9.1.5 Simulations

This thesis work focused on non-linear static simulations in Hypermesh software and Optistruct solver. It would be possible to obtain accurate results if the dynamic simulations were investigated. However, in the initial stage of the thesis work, dynamic simulation in Ansys was performed but unable to obtain results because of license limitations of 512K cells/nodes.

In the simulation setup, 250 kN force was assumed to be the side pole force acting on a simplified section of the battery housing. Even though the large value of side pole force was acted on the sill beam of the battery housing, a small value of static

force 250kN was considered for the simplified section so that the post-processing results can be extracted from the simulation of different models and comparison can be done with the same input force value.

The simulations only involved the side pole load acting on the bottom plate where the point of application of load is between two cross beams. If the application of crash load is done on the cross beams directly, the results would have changed and the design for safety of cross beams would have been higher which creates the need for a robust design for cross beams.

The thesis work only involved weight reduction, material cost reduction, and addressed crash safety parameters for side pole crash load cases. It didn't address other aspects such as durability, Noise Vibration Harshness (NVH) performance, and other load cases such as front, rear, and spoc load case which needs to be balanced.

According to the decided simulation setup, the obtained results were investigated for a simplified battery housing model in this thesis work. If the simulation setup is modified by varying different parameters, the results would have obtained differently. Various parameters such as type of crash load case, type of simulation software, type of simplified model can be altered to investigate different focus areas in the battery housing.

Within the decided simulation setup, various parameters like mesh size, etc in the Hypermesh software can be altered which can influence the obtained results in this thesis work.

9.1.6 Opportunities for further development of final concept

This section discusses various opportunities that can be further developed by Volvo cars to make the final concept into a fully functional model as similar to the existing concept.

- The intrusion loss of 28% in the final concept compared to the existing concept was calculated for the simplified section. If it is calculated for whole battery housing, intrusion loss might be high at the joining of the section. This intrusion loss of 28% is important as it affects the whole battery housing because the side pole load is multiplied during the crash analysis. Hence the final concept shall be redesigned towards the crash safety aspect to reduce the intrusion loss.

- The final steel concepts can be redesigned or optimized further by topography and gauge optimization (thickness optimization), this will give an opportunity for weight reduction and improvement in crash safety parameters (intrusion and displacement in Z).

- Bead height of the final concept bottom plate is equivalent to that of existing aluminum bottom plate thickness. There is an opportunity to reduce the height of the bead, maintaining the module weight displacement in z-direction equivalent to Volvo Car standards.

- Replacement of existing aluminum sill beam and casting with steel sill beam and casting, and joining bottom plates and cross beam though welding can possibly enhance the crash performance, reduce the material cost, possibly enhance the volume of the battery pack by giving an opportunity to add more number of battery modules, and to possibly optimize the overall weight of battery housing.

9.2 Conclusions

The conclusion aims at addressing the research questions stated in the section 1.6.

RQ1: What are various ways of achieving weight reduction in the existing components of battery housing such as bottom plates and cross beams?

To conclude the discussion, the thesis work investigated various possibilities of achieving weight reduction in the existing components of battery tray carrier such as bottom plates and cross beams by performing topology and topography optimization of concepts. The exploration of potential was successfully done even though it was not reflected in the results.

RQ2: What are the different ways of designing structures that address side pole safety criteria of crash analysis set by Volvo cars?

The thesis work showcased various ways of designing safe structures for crash loading in the concept development chapter. Multiple iterations of simulation-driven designs were performed to design the bottom plate which performs well at crash safety parameters. The iterations included varying shapes, location, height, and thickness parameters of beads on the bottom plate.

RQ3: How are the materials chosen for the design of components in the battery housing such as bottom plates and cross beams to reduce weight, cost, and withstand crash loading?

The thesis work involved detailed materials selection process for the design of components in battery housing such as bottom plates and cross beams to reduce weight, cost, and withstand crash loading in the material study chapter. The established parameters for the selection process were strength to weight ratio, material cost, and sustainability to align with the objectives of weight reduction, material cost reduction, and withstand the crash loading.

The conclusions drawn from the results were briefly discussed below:

- The thesis work obtained a financially attractive steel concept design with 65.4% material cost reduction.
- The final concept reduced the number of bottom plates into single or few plates which can be advantageous in few aspects.
- 6.3% extra weight per section of steel concept has the potential to get reduced and crash performance can be improved by further iterations of redesign which can make the concept equivalent to SPA2 concept.
- Steel is an opportunity for e-mobility to be affordable, safer and sustainable (environmental aspect).

10
Future work

This chapter discusses the future work which is needed to be carried out by Volvo cars after this thesis work.

- The final steel concept which consists of bottom plates and the cross beam can be bonded using adhesive material to integrate into the existing aluminum sill beam. Although, the adhesive bonding is expensive when compared to welding, adhesive bonding is suitable as the welding of steel and aluminium is challenging due to the different melting temperatures of both materials. Using the adhesive bond as a joining method, battery housing shall have aluminum sill beams and aluminum Castings integrated with steel cross beam and steel bottom plates.

- Detail design of final steel concept cross beam which includes developing trigger point, weld nuts, and bolt holes, gives the potential opportunity to reduce weight and enhance the crash performance.

- For further development of the final steel concept, other attributes such as NVH performance, durability, front, bottom, spoc, rollover, rear load case, and side-impact force acting on the cross beam has to be balanced.

- A flat bottom sheet made of plastic is required to cover the below portion of final concept bottom plate to prevent corrosion and improve the aerodynamics. In this way, the material accumulation on the beads shall be prevented.

- As the cross beam and bottom plate are made of steel, there are additional challenges such as corrosion which needs to be addressed. The corrosion resistance painting has to be used in the similar way Chevrolet Bolt EV addressed this challenge.

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A

Appendix - Interview guide

1. Thyssenkrupp Steel Europe industries - This consultation was conducted to understand their work on Battery Housing development using Steel and Aluminium, to determine different grades of Steel, estimate the performance of Sandwich materials, identify the pros and cons of using Steel and their approach in solving sustainability challenge.

- *Expert at Thyssenkrupp briefly illustrated the advantages of using Steel instead of Aluminium material, because it is light in weight (battery housing as a complete structure), less expensive in terms of material cost and manufacturing cost, high crash performance and suitability for mass production. Also, it has excellent electromagnetic compatibility, high protection from fire, low production waste (because of rolled profiles). However, he also stated the underlying problem such as tolerance, tooling investment cost and corrosion problems, but corrosion problems can also be solved by chromium coating.*

- *He also stated the problems associated in Sandwich material, and Honeycomb structure, which are large and occupies more space. Additionally, Hybrid structures performance was not good enough, as it is expensive and consumes more space.*

- *Different grades of high strength materials which are available in the market are CP-W 660Y760T, DP-K 590Y980T, and MS-W 900Y1180T. Among them, Cold forming steel DP-K 590Y980T has excellent compromise between intrusion and energy absorption. Using Steel as a solution can save upto 65% of CO2 emission during production when compared to Aluminium*

2. Chalmers and Jönköping solar team - This interview was conducted as they have developed a compact battery system with Small BMS which increases packaging efficiency to compete for World Solar Challenge 2021. Additionally, to understand their choice of material used for Battery housing development.

- *Project team used material which is stiff and stamped aluminium with corrugated shapes, and next is to determine the forces which withstand the impact.*

- *They recommended us to look for weight-saving material such as Carbon fiber, glass fiber, Polycarbonates, Aluminium/Steel with glass fiber. Also, focusing more on different alloys of Aluminium and contacting Suppliers will be a good option, because the availability of materials and manufacturability of the design has to be analyzed with the suppliers.*

3. Smart Bratt team, Research Institute - This interview was done to understand their 8 years of research on Battery housing development using sandwich materials. Also, to gather data on their findings and a contact person who is responsible for Battery housing design.

- *They shared their research findings about Aluminium foam sandwiches and APM hybrid foams (aluminium foam spheres bonded by epoxy foam).*

- *They suggested to increase service efficiency in terms of plugs disconnection, easy removal and access of battery pack. And also, to improve sealing of housing in battery pack.*

4. Expert at ETH Zurich - This interview was conducted to know about one of the ideas i.e. Adaptive Structures which was developed during Idea generation phase. One of the ideas during concept generation was to integrate this structure into the Battery Housing to improvise the packaging efficiency. Inorder to know about the insights on implementation of Adaptive structures in the cars, this interview was performed.

- *He was uncertain of implementations of adaptive structures on Battery housing because of limited structural analysis results.*

- *His inputs on Stiff structures and Load absorbing structures such as E and L shape panels was valuable. In addition, he assisted in building the contacts with 9T lab (composite startup organisation) and recommendations on corrugated glass fibre structures, and sandwich structures*

B

Appendix - Competitors Benchmarking

This section involves benchmarking data tables where the comparison of competitors was done against several criterias and comparable ratio known as energy density was compared at the last row of table

Criteria of Battery Housing	Audi E tron 55	Hyundai Kona
Comparision criteria		
Model Year	2019	2018
Market	UK, Europe	UK, Europe
Dimensions of Battery Tray(L-W-H)	2160mm-1625mm-140mm	1970-1440-310
Volume of Battery tray (litres)	490	879
Dimensions of Battery Lid(L-W-H)	2105mm-1410mm-57mm	1780mm-1290mm-260mm
Volume of Battery lid (litres)	169	597
Dimensions of vehicle (Length - width - Height)	4901mm-1935mm-1616mm	4180mm-1800mm-1570mm
Total Volume of vehicle (litres)	15325	11812
Wheel base of vehicle	2928mm	2600mm
Range of vehicle	355 Km	400km
Weight of Battery carrier (Kg)	99	67
Weight of Battery Lid (Kg)	11.3	15
Total weight of the battery system	681	450
Total weight (Empty) of vehicle(kg)	2490	1685
Battery voltage (V)	396	356
Battery Capacity (Ah)	240	180
Battery Energy (kW-h)	95	64
Number of Modules in BH	36	10
Weight of Modules in BH	472,6	244, 366
Comparable ratio ((kW-h)/kg)	13.95	14.22

Figure B.1: Benchmarking data of Audi E tron 55 and Hyundai Kona

Criteria of Battery Housing	Jaguar I pace	NIO ES8	Volkswagen e-Golf	Nissan leaf SV
Comparision criteria				
Model Year	2018	2019	2018	2017
Market	Europe	China	UK, Europe	North America
Dimensions of Battery Tray(L-W-H)	2310mm-1455mm-156mm	2060mm-1542mm-133mm	2312mm-1160mm-60mm	1540mm-1126mm-335mm
Volume of Battery tray (litres)	520	420	160	580
Dimensions of Battery Lid(L-W-H)	2233mm-1303mm-58mm	1725mm-1359mm-8mm	2130mm-1040mm-22mm	1440mm-1011mm-182mm
Volume of Battery lid (litres)	160	18	48	260
Dimensions of vehicle (Length - width - Height)	4682mm-2011m-1565mm	5022mm-1962mm-1756mm	4270mm-1799mm-1450mm	4445mm-1770mm-1549mm
Total Volume of vehicle (litres)	14735	17302	11,138	12186
Wheel base of vehicle	2990mm	3010mm	2631mm	2700mm
Range of vehicle	370 km	355Km	190km	172 km
Weight of Battery carrier (Kg)	75	97	50	45
Weight of Battery Lid (Kg)	11	13	13	10
Total weight of the battery system	603	523	344	290
Total weight (Empty) of vehicle(kg)	2133	2460	1540	1507,2
Battery voltage (V)	389	350	323	360
Battery Capacity (Ah)	232	200	122.1	82
Battery Energy (kW-h)	90	70	35.8	30
Number of Modules in BH	36	32	7	24
Weight of Modules in BH	429	170	487,172	218
Comparable ratio ((kW-h)/kg)	14.93	13.38	10.41	10.34

Figure B.2: Benchmarking data of Jaguar I pace, NIO, Volkswagen e-Golf and Nissan leaf SV

Criteria of Battery Housing	Tesla model S 60	Chevrolet Bolt EV	Tesla model 3 Standard	BMW i3 eDrive range extender
Comparision criteria				
Model Year	2013	2017	2018	2014
Market	Europe	North America	USA	North America
Dimensions of Battery Tray(L-W-H)	2616mm-1524mm-104mm	1815mm-1275mm-387mm	2156mm-1470mm-122mm	1585mm-890mm-160mm
Volume of Battery tray (litres)	410	895	386	225
Dimensions of Battery Lid(L-W-H)	2380mm-1455mm-36mm	1815mm-1058mm-305mm	1740mm-300mm-75mm	1589mm-895mm-18mm
Volume of Battery lid (litres)	120	585	39	25
Dimensions of vehicle (Length - width - Height)	4970mm-2037mm-1445mm	4165mm-1765mm-1595mm	4692mm - 1853 mm- 1446mm	3987mm-1778mm-1574mm
Total Volume of vehicle (litres)	13991	11,725	12571	11,157
Wheel base of vehicle	2960mm	2600mm	2875mm	2565mm
Range of vehicle	345km	238 km	402km - 518 Km(Long range extender)	130km
Weight of Battery carrier (Kg)	100	66	51	25
Weight of Battery Lid (Kg)	27	14.78	18.6	4 .858
Total weight of the battery system	500	427	460	233.26
Total weight (Empty) of vehicle(kg)	2010	1624	1741	1297
Battery voltage (V)	350	355	350	362.9
Battery Capacity (Ah)	204.8	180	214	60
Battery Energy (kW-h)	62	60	75	22
Number of Modules in BH	16	10	4	8
Weight of Modules in BH	138,4	426.6	188.7	230
Comparable ratio ((kW-h)/kg)	12.40	14.05	16.30	9.43

Figure B.3: Benchmarking data of Tesla model S 60, Chevrolet, Tesla model 3, BMW i3

Criteria of Battery Housing	BMW i3 eDrive range extender	BMW i3 range extender	Tesla Model X (P90D)	Mitsubishi i-MiEV
Comparision criteria				
Model Year	2014	2019	2016	2011
Market	North America	North America	North America. Europe	Europe
Dimensions of Battery Tray(L-W-H)	1585mm-890mm-160mm	1660mm-964mm-157mm	2730mm-1559mm-108mm	1384mm-720mm-180mm
Volume of Battery tray (litres)	225	250	459	180
Dimensions of Battery Lid(L-W-H)	1589mm-895mm-18mm	1586mm-895mm-20mm	2495mm-1455mm-95mm	1386mm-723mm-73mm
Volume of Battery lid (litres)	25	28	340	70
Dimensions of vehicle (Length - width - Height)	3987mm-1778mm-1574mm	4020.82mm-1775mm-1597,6mm	5036mm-2070mm-1684mm	3395mm-1475mm-1600mm
Total Volume of vehicle (litres)	11,157	11,402	17,554	8012
Wheel base of vehicle	2565mm	2570,48mm	2965mm	2550mm
Range of vehicle	130km	246km	375km	100km-160km
Weight of Battery carrier (Kg)	25	23	96	22
Weight of Battery Lid (Kg)	4 .858	5	29	6
Total weight of the battery system	233.26	275	576	224
Total weight (Empty) of vehicle(kg)	1297	1485,96	2439	1080
Battery voltage (V)	362.9	352.5	345.6	325
Battery Capacity (Ah)	60	120	237	49
Battery Energy (kW-h)	22	42	90	16
Number of Modules in BH	8	8	15	12
Weight of Modules in BH	230	207,585	376.59	64,685
Comparable ratio ((kW-h)/kg)	9.43	15.27	15.62	7.14

Figure B.4: Benchmarking data of BMW i3 range extender, Telsa model X and Mitsubishi

C

Materials Benchmarking

This chapter involves material benchmarking data gathered from various sources such as literature data, competitors benchmarking, interviews and CES Edupack.

Properties		Density (kg/m3)	Yield strength (Mpa)/ Elastic limit	Modulus of Elasticity [GPa]	Tensile : UTM (Mpa)	Elongation %	Elastic stored energy KJ/m3	Cost (SEK/Kg)	Poisons ratio	thermal properties (W/m. deg C)	Max service temperature (Deg C)	Melting range (Deg C)	Electrical Conductivity [MS/m]	Primary prodcution energy, CO 2 (Kg/Kg)
Aluminium 518 die cast F		2.50E+03	177	69.6	310	8	220	19.5	0.3	96.4		517	2.36E+01	14.7
Al 2008T62		2.69E+03	228	68.3	285	12	371	19.6	0.32	161	130	610	4.11E+01	12.3
Al 5083 H323		2.64E+03	234	70	310		381	19.5	0.33	117		574	2.85E+01	2.58
Al 5182 H19		2.63E+03	373	68.5	400	3.7	989	19.4	0.32	118		577	3.04E+01	13.7
DP-W® 300Y530T	Selectrify		300-450		530	25								
FB-W® 300Y450T			300-420		450	27								
DP-W® 700														
DP-K® 440Y780T					800									
CP-W® 660Y760T			660-830		760	12								
DP-K ® 590Y980T			590-740		980	--								
MS-W® 900Y1180T			900-1070		1180	--								
AL APM Aradlite Steel	Research : Volkswagen, RISE (SP), AIT	1.45E+03	-	1300	-			80	---	---	---	---	---	---
AL APM Aradlite Al		8.16E+02	-	600	-			80	---	0,44	---	---	---	---
AL APM Aradlite		1.44E+03	-	1162	-			80	---	---	---	---	---	---
AL APM Aradlite		9.40E+02	-	-	-			80	---	0,4	---	---	---	---
AFS (roll clad)		6.70E+02	120	5000	120			120	---	7	---	---	---	---
AFS (roll clad)		8.10E+02	120	5000	120			120	---	---	---	---	---	---
TPO (PP+EPD)M Shore a75		861	4.78	0.015	4.78		571-1330	15.5				141-163	8,8e-19	4.32
Honey comb materials														
ABS Foam		840	20	1.2		3		29.6	0.25	0.7	67		1.72E-20	
Stainless steel HC 301		83	0.00514	1.26E-04	0.194		0.8	357	0.44	0.189		1000	2.00E-01	9.52

Figure C.1: Material Benchmark - A

Properties		Temper	Density (kg/m3)	Yield strength (Mpa)/ Elastic limit	Bending stiffness and Flexural	Modulus of Elasticity /Youngs modulus [GPa]	Tensile : UTM (Mpa)	Compressive strength Mpa	Elongation %	Cost (SEK/Kg)	thermal properties (W/m. deg C)	Max service temperature (Deg C)	Melting range (Deg C)
AL APM Aradlite Steel	Research : Volkswagen, RISE (SP), AIT	0.5-4-0.5	1.45E+03	-	5,32e8	1300	-	4,2		80	---	---	---
AL APM Aradlite Al		0.5-4-0.5	8.16E+02	-	3,54e8	600	-	2,9		80	0,44	---	---
AL APM Aradlite		0.5-4-0.5	1.44E+03	-	5,32e8	1162	-	4,1		80	---	---	---
AL APM Aradlite		0.5-4-0.5	9.40E+02	-	3,54e8	-	-	5		80	0,4	---	---
AFS (roll clad)		0.75-8.5-	6.70E+02	120	22,5e8	5000	120	4		120	7	---	---
AFS (roll clad)		1,0-10-1	8.10E+02	120	42,4e8	5000	120	4		120	---	---	---

Figure C.2: Material Benchmark - B

Properties		Density (kg/m3)	Yield strength (Mpa)/ Elastic limit	Modulus of Elasticity [GPa]	Tensile : UTM (Mpa)	Elongation %	Elastic stored energy KJ/m3	Cost (SEK/Kg)	Poisons ratio	thermal properties (W/m. deg C)	Max service temperature (Deg C)	Melting range (Deg C)	Electrical Conductivity [MS/m]	Primary prodcution energy, CO 2 (Kg/Kg)
Alumnium alloy		2.66 e3 - 2.72 e3	170 - 198	68	---			19.3 - 22.5	0.325	197 - 205	130 - 150	630	29.41 - 31.26	12.5
Alluminium alloy		2.68E+03	184	68	222			19.3 - 22.5	0.32	185	130	630	48.3	12.4
Al		2600	140	72	220	13	150	22	0.33	140	170	600	38	
AlMgSi (wrought)	Audi E tron 55	2.700 e3	120*	70	190			19.3 - 22.5	0.325	200-220	130 - 150	585-650	28-34	12.4 - 13.7
AlMgSiMn		2.700 e3	250	70	290			---	0.33	200-220	160	585-650	28-34	
AlSi10MnMg Casted (Aluminium extruded		2.6	170	72	300			---	0.33	140	170	600	22.04	7.8
Plastics PP-GF40	Mitsubishi	1.21E+03	60	6.01				17	0.3	0.352	63	175	very less	1.75
HYBRIX	CFS	---	800	200	1400			---	---	0,08	---	---	---	---
Be-Al alloy		2.07 e3	193	179	262	2-10.3	104	3400	0.165	240		640	48	513
Magnesium mg 30% B4C		2 e3	260	65	310	0.5-1	493	179		70		510	19.4	34
Polymer Pheolic/E-glass fiber		1.7 e3	217	27.2	217	0.55-1.9	817	230	0.77	0.72			1.2 e-18	6.08
polyester /E-glass fiber (Thermoset)		2.02E+03	50	15	50	0.45		16.2	0.13	0.655	112		2.30E-21	4
Polyester/E-glass fiber pultruded rod		1.90E+03	690	35	690	2	5.84E+03	15.5	0.33	0.182			1.72E-05	4.16
polyester SMC		1.73 e3	145	11.8	145			32	0,273	0.79			1.57E+17	1.56
Alumino silicates 1720		2.49E+03	39.9	84.8	39.9	0.04	9.15	12.4	0.23	1			1.72E-23	0.891

Figure C.3: Material Benchmark - C

Properties		Density (kg/m3)	Yield strength (Mpa)/ Elastic limit	Modulus of Elasticity [GPa]	Tensile : UTM (Mpa)	Elongation %	Elastic stored energy KJ/m3	Cost (SEK/Kg)	Poisons ratio	thermal properties (W/m. deg C)	Max service temperature (Deg C)	Melting range (Deg C)	Electrical Conductivity [MS/m]	Primary prodcution energy, CO 2 (Kg/Kg)
Aluminium 3003 HC		22	0.002	1.91E-05	0.003			118	0.442	1.27		343	1.80E-01	23.6
Aluminium SiC foam		64	0.25	4.50E-01				184		0.5		550	2.70E-01	20.8
cast iron AISI 1080		6.90E+03	65	80	100		24.2	2.47	0.55	50		#######	2	
Cast iron nodular graphite EN GJS 350 22		7.05E+03	215	165	350		138	2.382-3.79		36		1130		
Cast iron austempered ductile ADI 1050		7.00E+03	730	160	1050			2.73-4.15		21	350	1100	2.92	2.26
Aluminium 7037 T7452	AL 87 percent, zinc 9 percent	2.85E+03	421	68.3	476	8			0.33	154	80	524	40.1	12
Magnesium, commercial purity ASTM 9980A		1.17E+03	65	44	175	12 TO 20	49	19.8	0.28	150	150	642	34.5	44
Soda lime 0070		2.47E+03	30.3	68	30.3			12.4	0.21	0.7	201		1.72	0.7
silica 96		2.15E+03	152	66.3	152	0.22		53	0.18	1	900		1.72E-23	2.25
Kevlar 29 aramid fiber		1.40E+03	2500	62	2900		4.31E+04	216	0.35	0.2	200	497	1.72E-19	16.4
kevlar 149 aramid fober		1.46E+03	2.50E+03	170	3200	1	17000-25000	789-2000	0.35	0.2	200	500	1.72E-19	16.4

Figure C.4: Material Benchmark - D

Properties		Density (kg/m3)	Yield strength (Mpa)/ Elastic limit	Modulus of Elasticity [GPa]	Tensile : UTM (Mpa)	Elongation %	Elastic stored energy KJ/m3	Cost (SEK/Kg)	Poisons ratio	thermal properties (W/m. deg C)	Max service temperature (Deg C)	Melting range (Deg C)	Electrical Conductivity [MS/m]	Primary prodcution energy, CO 2 (Kg/Kg)
press hardening steel, 22Mnb5 austenized and H20 QUENCHED coated		7.80E+03	990-1210	200	#####	5.4-6.6%	2300	6.7	0.29	42		1400	5.95	2.81
Stainless steel ferrite ASTM CC 50, low ni		7450	400	196	430	1 to 3	404	15	0,275	15	760	1500	2,1	3,4
Stainless steel ferritic High nicekl		7450	365	196	590	4 to 22	340 to 601	17	0,275	17	760	1500	2,1	3,61
Alloy steel 9Cr-1MO, grade F9		7700	379	207	586	18 to 24	676	15	0,27	22,1	1070	1500	6,38	2,2
Bake hardening steel cold rolled YS260		7800	260	200	360	29 TO 36	162	6,53	0,286		291	1400	5,95	2,18
Dual phase steel ys450 cold rolled		7800	450	200	780	14	485	7	0,29	42	473	1420	5,95	2,73
Dyal phase steel ys600 cold rolled	0,06-0,23	7800 - 7900	600 - 750	200 - 221	980 - 1100	15	863 to 1300	7,15 - 7.5	0,286 - 0.315	42	473	1420	5,95	2,73
high strength low alloy stel YS550 cold rolled		7800	550	200	600	12	721 to 1010	6,53	0,286	42	473	1420	5,95	2,49
Martensitic steel YS1200 hot rolled		7800	900	200	1200		1950	8,38	0,286	42	473	1500	5,95	2,75

Figure C.5: Material Benchmark - E

D

Appendix - Requirements specification

	Product Specific Requirement	Target values	Set by	Verification
1	**Cost**			
	R1 - Material cost	Less than the or equal to existing material cost	Volvo cars	CES Edupack
2	**Safety**			
	a) Mechanical			
	R2 - Intrusion	Displacement in Y direction less than 1mm	Volvo cars	Simulation
	R3 - Bending	Displacement in Z direction less than 0.5mm	Volvo cars	Simulation
	R4 - Stress	Below the Ultimate strength of the material	Volvo cars	Simulation and CES
	b) Electrical			
	R5 - Electrical insulation (Resitant to electrical shocks)	Less than the or equal to existing material	Volvo cars	CES Edupack
	R6 - Electromagnetic compactability : Avoid the interactions from the surrounding electronics	Less than the or equal to existing material	Volvo cars	CES Edupack
	R7 - Electromagnetic Interference: Avoid the interactions to the surrounding electronics	Less than the or equal to existing material	Volvo cars	CES Edupack
	c) Material fuctionalities			
	D1 - Thermal conductivity	Less than 200 (W/m.°C)	Volvo cars	CES Edupack
	D2 - Melting point	More than 630 °C	Volvo cars	CES Edupack
	D3 - Corrosion resistant	withstand corrosion	Volvo cars	CES Edupack
	d) Thermal			
	R8 - Thermal Insulation	Able to withstand the fire release and fluid release	Volvo cars	CES Edupack
3	**Weight and Geometry**			
	R9 - Total weight	less than Akg	Volvo cars	Simualtion
	R10 - Geometry -(LxWxH)	Equal to the Existing SPA2 concept	Volvo cars	CAD
4	**Manufacturability and assembly**			
	a) Manufacturable			
	R11 - Manufacturability	Design for Manufacturing	Thesis team	CAD design
	b) Assembly			
	D4 - Assembly constraints	Design for assembly	Volvo cars	Assembly
	D5 - Number of Components	Less component than Existing SPA2 concept	Thesis team	CAD design
5	**Environment**			
	D6 - Recyclable	More or equal to the Existing SPA 2 concept	Thesis team	CES Edupack
	D7 - Usage of sustainable materials	Less or equal CO2 emission than the Existing SPA2 concept	Volvo cars	CES Edupack

Figure D.1: Requirement Specification

E

Appendix - Idea generation

This chapter involves morphological matrix where the ideas were generated from sub-functions of function means tree and also discusses few concepts at the end.

E.0.1 Morphological Matrix

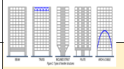
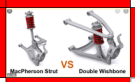
Sub- function	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6	Alternative 7	Alternative 8	Alternative 10
To Mount the components	IAP FITS	Anti vibration fixtures - pads, screws etc	METAL INSERTS	ELASTOMERS(take high loads, save space)	modules mounted to the nearest cross beams (draw & explain)	Integrate Cross beams, bottom plates into one component which can serve both functions and mount the battery modules. (draw & explain)	lego interfaces	rivet	Welding
Withstand structural load / Absorb the load			Concrete beam	symmetrical geometrical links in structures like Jaguar I-pace.	Foam or Honeycomb materials	T-beams	Ribs or stiffeners added to structures	 Tranfer beams or truss structures in bridges	off shore structures from ship (yet to be developed)
Strutural Load distribution (Or load transfer)	Hydraulics	hinge	 MacPherson Strut VS Double Wishbone	Bridge	Links (frames)	Load transfer through medium like coolant - Tesla (Torbjorn explained)			
Buckle at high load	Bend section - V section	Maxium material removal in trigger point - let it buck at high load	Trigger point of Air bag release when high load is acted						
Protect battery module	Enclosure	structural cage around modules (sketches yet to be developed')	energy absorbing trap around modules which can absorb the high loads. (sketches yet to be developed)	Structures - Pushing away the incoming load. (sketches yet to be developed)	structures - deviating the load path -like spoc function	fill battery modules space with dry ice / solid co2	auto shut down of modules before impact about to happen	components in chassis which deviates the loads incoming to the battery	use of advanced materials: tensile filaments that act in case of collision, thermosets broken links which act by absorbing the impact energy generated in the fiber and combined with high strength composite metal / polymer composite micro /
Heat prevention material	Replaceable plate	Cold not accepting in the winter: material (magic material)							
Heat dissipating strutures	Fins	thin flat metal sheets	Heat exchangers	Holes	Cladding structure	Heat not taking material (magic material)			

Figure E.1: Idea generation table - A

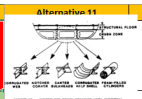
Sub- function	Alternative 11	Alternative 12	Alternative 13	Alternative 14	Alternative 15	Alternative 16	Alternative 17	Alternative 18	Alternative 19
To Mount the components									
Withstand structural load / Absorb the load	structures(energy aborbing joint concept)	Air bag technology for absorbing load.	Triangulated structures	Cast iron	Bloating bag	Anvil	Suspension	Chassis	Lever
Strutural Load distribution (Or load transfer)	tranfer to trigger point in case of high load								
Buckle at high load									
Protect battery module	anti intrusion plates surrounding modules	Foam/wood	Battery pack disconnect from the car, have the wheels and slide on the road.	Sand	rubber				
Heat prevention material									
Heat dissipating strutures									

Figure E.2: Idea generation table - B

Sub- function	Alternative 20	Alternative 21	Alternative 22	Alternative 23	Alternative 24	Alternative 25	Alternative 26	Alternative 27	Alternative 28
To Mount the components									
Withstand structural load / Absorb the load	Alnzino steel	Concept of adaptive multi-folding micro-structures	extrusions - structures having hydraulics between plates	hydraulics in cross beams - compressing during taking loads Auto shutdown on IMPACTS	Passive protection systems which can absorb load during collisions	Impact attenuators from formula student. Mount similar structures on surroundings of battery pack. (absorb load because of foam or cans, or Honeycomb structures)	Long Fiber Reinforced Thermoplastic Composite (LFRT)	Redirective Attenuator	
Strutural Load distribution (Or load transfer)									
Buckle at high load									
Protect battery module									
Heat prevention material									
Heat dissipating strutures									

Figure E.3: Idea generation table - C

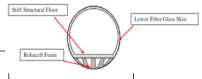
Sub- function	Alternative 28	Alternative 29	Alternative 30	Alternative 31	Alternative 32	Alternative 33	Alternative 34	Alternative 35	Alternative 36
To Mount the components									
Withstand structural load / Absorb the load		V BEAM GUARD RAILS	Rohacell 110IG foam	Water filled attenuators	sand filled barrels	crash cushions	Pyrotechnically controllable adaptive system	brittle fiber materials like carbon or glass in combination	thin walled structures
Strutural Load distribution (Or load transfer)									
Buckle at high load									
Protect battery module									
Heat prevention material									
Heat dissipating strutures									

Figure E.4: Idea generation table - D

Sub- function	Alternative 37	Alternative 38	Alternative 39	Alternative 40	Alternative 41	Alternative 42	Alternative 43	Alternative 44	Alternative 44	Alternative 45	Alternative 46	Alternative 47
To Mount the components												
Withstand structural load / Absorb the load	corrugated panels	Polymer foam-cored sandwich composites	Dome shaped structures	Gelatin	Sorbothane material (polymer)	Landing gear	Structural deformation			Crash resistant barrier net - Kevlar webbing		
Strutural Load distribution (Or load transfer)												
Buckle at high load												
Protect battery module												
Heat prevention material												
Heat dissipating strutures												

Figure E.5: Idea generation table - E

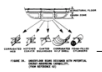
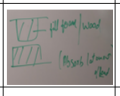
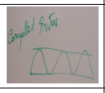
Sub- function	Alternative 48	Alternative 49	Alternative 50	Alternative 51	Alternative 52	Alternative 53	Alternative 54	Alternative 55	Alternative 56	Alternative 57
To Mount the components										
Withstand structural load / Absorb the load	High speed solenoids	Foam filled cylinders	Notched corners	Corrugated half shell						dampers
Strutural Load distribution (Or load transfer)										
Buckle at high load										
Protect battery module										
Heat prevention material										
Heat dissipating strutures										

Figure E.6: Idea generation table - F

Heat dissipating strutures	Fins	thin flat metal sheets	Heat exchangers	Holes	Cladding structure	Heat not taking material (magic material)			
Enable easy access to remove the component	temporory fastening like screws, for easy removal by technicians	service lid - in easy access for technicians. - Positions like - below rear seats, below the car etc	voltage disconnection switch and safety precautionary switches to be provided in case of access to technicians.	Digitally monitored overhauling for technicians.					
	Sub-functions necessary for the material selection								
Insulate the components from high temperature	Lamera material		Ceramic fibre material	Intumescent Coatings for steel	bomb suit	water	sand	fibre gloss cloth for exhaust	teflon sheet
Insulate the components from Electrical loads	Plastic material	Kevlar	Electrical hand holder	Low electrical conducting material	Casting resins	resistors	transformers	switch	brake circuit
Insulate material for electromagnetic compactability	Surface mount devices SMD	EMC shielding gaskets	conductive mask tape EMC	EMC conductive paints	Polymer based composites	foams and aerogels	pre tin plated steel	copper	
Heat dissipating material	aluminium alloys	copper	brass						

Figure E.7: Idea generation table - G

Heat dissipating strutures									
Enable easy access to remove the component									
Insulate the components from high temperature	silica cloth	trapping air materials							
Insulate the components from Electrical loads	Aluzinc material	fuse							
Insulate material for electromagnetic compactability									
Heat dissipating material									

Figure E.8: Idea generation table - H

Here are the few concepts which were not discussed in detail in the report.

E.0.2 Bottom plate dynamic concept for environmental conditions

This concept was developed to address the main problem i.e thermal conduction in hot and cold environment condition which is explained in detail in section **??**. Dynamic Plate which is in zigzag shape flips 90 degree gives more contact surface to the environment allowing them to take away the heat generated from the Battery. In a similar way, when it flips in the opposite 90 degree direction, it restricts the heat

conduction. In this way, depending on the hot and cold climatic conditions based on the geographic locations, the battery can maintain the operating temperature of 15 degree to 35 degree within the battery pack.

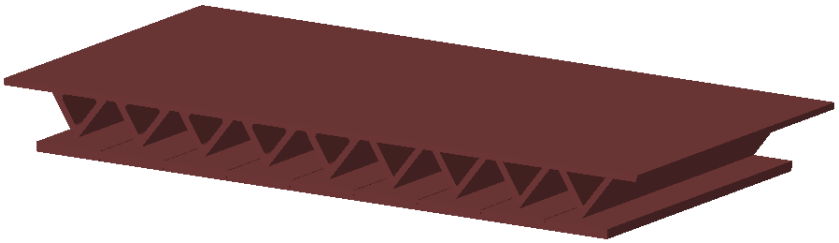


Figure E.9: Bottom plate dynamic concept for environmental conditions

E.0.3 Integrated sill beam and cross beam concept

This concept integrates both sill beam and cross beam. The cross beam is made of I shape at both the ends. Accordingly, a cut out is made in the sill beam for the cross beam to integrate into it. This integration can be similar as the existing cross beam and sill beam but can consume some space which is allocated for the battery modules between cross beams. This concept is eliminated as it has few limitations with manufacturing feasibility and design space constraints.

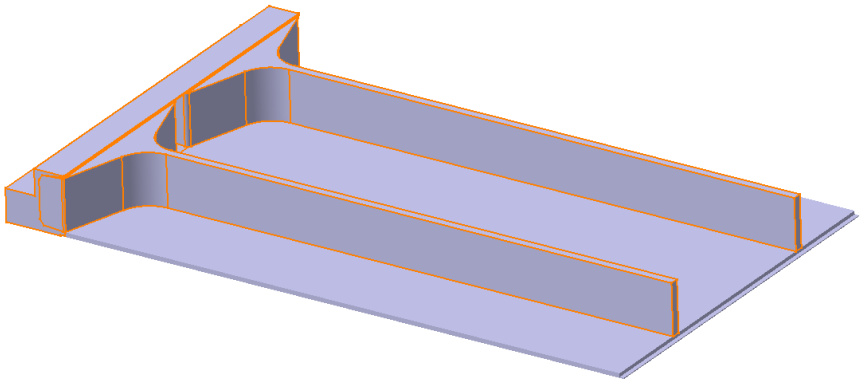


Figure E.10: Integrated sill beam and cross beam concept