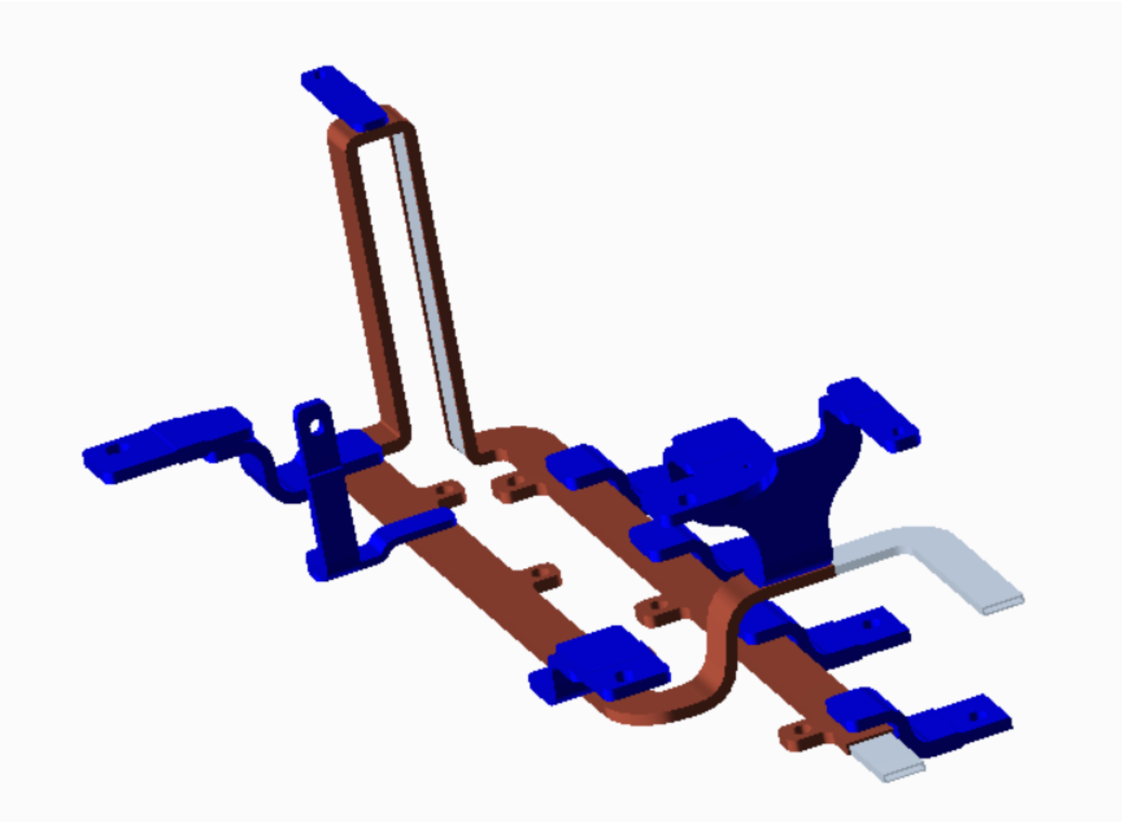

Commercial Vehicles Busbar Cooling Concepts

Master's thesis in Product Development

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MASTER'S THESIS 2023

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Abstract

With the paradigm shift in transport, the emergence of sustainable technology has gained emphasis over the past few years. In an effort to create an emission-free world, BEVs are focused, and electric trucks are no exception. The heavy need for power in trucks leads to the overall heating of the busbars and, eventually, a gradual loss in current carrying capacity. The integration of a cooling concept along with busbars adds to the power junction box's weight, cost, and performance and serves as the project's background. There is a need to effectively cool down busbars and increase their operating temperature while considering weight and cost parameters.

The project follows a systematic product development approach from requirement specification to concept selection and prototyping of the selected concept. The process was applied to redesign and optimize the existing cooling concept for busbars at Volvo Trucks in terms of material selection, concept design, and performance, accompanied by the simulation to validate the results. Various concepts for cooling were explored and mapped out in the idea-generation table, with the decision to pursue further development of direct liquid cooling accompanied by different cross-sections and material selection for the busbars. These comprehensive results are further justified through thermal and fluent simulations to evaluate the maximum temperature, thermal conductivity, and safety.

The final concept consists of a C-shaped busbar attached to an aluminum coolant tube underneath it. The hollow geometry profile of the aluminum tube enables direct cooling while being insulated with an electrical insulation layer to prevent contact between the coolant and the current-carrying copper busbar. The final concept achieved a reduction of 18.8% in the maximum temperature of the busbar. The final design also attained a weight of 45.4% compared to the existing design due to the employment of aluminum material. The material cost is reduced as the solid copper busbar is replaced with copper and a cheaper material option of aluminum, constituting the same electrical density while minimizing the weight. Hence, the thesis has validated employing a direct cooling method with proper material combinations and safety considerations to improve the cooling efficiency in a busbar.

Keywords: busbar, cooling, simulation, optimization, material selection, electric vehicles, product development, current capacity, thermal conductivity, safety, electric truck.

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Finally, we express our gratitude towards the entire electro-mobility team at Volvo Trucks for their companionship during the thesis and all other company members for the necessary support to kick start our thesis and provide a smooth transition till the end of the thesis.

Kaarthik Kotha and Wengeng Gao
Gothenburg, June, 2023

List of Acronyms

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

BES	Battery Energy Storage
BEV	Battery Electric Vehicle
BTMS	Battery Thermal Management System
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CCA	Copper Clad Aluminium
CCS	Combined Charging System
CFD	Computational Fluid Dynamics
DoE	Design of Experiments
ESS	Energy Storage System
EMD	Electric Motor Drive
EPTO	Electric Power Take-Off
FEM	Finite Element Methods
MCS	Megawatt charging System
NVH	Noise Vibration Harness
OCEPS	Onboard Charger and Electric Power Supply
PCB	Printed Circuit Board
PJB	Power Junction Box
REDS	Retardation Energy Dissipation System
SEK	Swedish Krona
TIM	Thermal Insulating Material
TVPDC	Traction Voltage Power Distribution Center

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1
Introduction

This chapter provides insight into the company and project background. Furthermore, it discusses the project's aim, objective, scope, and delimitations. The research questions are means of concept selection, and the report outline encompasses the report's structure.

1.1 Company Background

Volvo Trucks is a renowned world-leading truck manufacturing company in Sweden, headquartered in Gothenburg. It is a subsidiary of Volvo Group. Volvo Trucks is a global organization with Scandinavian roots but also has manufacturing, research, and design operations in Europe, America, and Asia. They strive to provide sustainable transport solutions ranging from medium to heavy-duty trucks with numerous customization's made available to the customers [1].

Volvo Trucks takes pride in its design towards sustainable and safe transport solutions. With the growing need for electrification, their business goal for 2026 is to lead in the safety, electrification, and personalization of their products in their market segment [2]. As mandated by the European Policy to shift the paradigm of transport to complete electrical solutions by 2040, Volvo Trucks are driving towards electrification, with significant developments in the battery design and thermal management of battery pack and their supporting modules, such as the junction box and cooling systems. They also aim to improve their supply chain, material reuse, and manufacturing methods to combat the rising CO_2 emission levels in the coming years [3].

1.2 Project Background

Generally, battery electric vehicles (BEVs) transmit current through busbars, consequently affecting the vehicle's performance. In the present scenario, Volvo Trucks are developing a new TVPDC box as part of their new product roll-out in the year 2025. As such, an opportunity is presented to redesign the existing cooling system to increase the battery output in busbars from 500A to 1000A while providing sufficient cooling to reduce the temperature in busbars.

Busbars are essential in electric vehicles as they distribute current more efficiently and flexibly than cables. They help in saving space and avoid the problem of tangling cables in vehicles. Also, they have more surface area than cables, which helps increase the current density through solid material. However, consequently, they are prone to heating due to the high current through them. Busbars are bound to have decreased electrical efficiency and current density without proper cooling systems [4]. Hence, there is a need to efficiently cool down the busbars while ensuring that other parameters, such as cost and weight, are significantly reduced.

1.3 Aim and Objectives of Thesis

The aim of this project is to develop an innovative cooling system for busbars that effectively lowers the operating temperature, resulting in increased current flow duration and improved efficiency of the Battery Electric Vehicle (BEV).

The master thesis aims to study and enable the future development of the existing cooling busbar system so that the battery pack and its integrated components can transfer higher power and current from the traction voltage system with minimal thermal heat generated. Also, increased heat in a busbar leads to more electrical resistance, eventually leading to a fire. Thus, safety is emphasized in this thesis.

Building upon Volvo Trucks' existing cooling concept for busbars, this project will propose design improvements. The focus is on finding an efficient method to distribute heat from the busbars, allowing for higher currents while minimizing power losses. The project will employ a holistic view of new design concepts, which will be evaluated and compared in terms of the following vital parameters, which will serve as the objectives for this thesis work:

- Weight reduction
- Material cost reduction
- Optimization of busbar dimensions
- Minimization of heat generation during vehicle operation

1.4 Project Scope

The project's scope was defined prior to the commencement of the thesis, with the objective of designing an efficient cooling system for busbars to dissipate heat and effectively reduce the operating temperature [5]. The busbars to be examined for cooling are a part of the Traction Voltage Power Distribution Center (TVPDC) box.

Various cooling methods were explored during the investigation phase, including direct and indirect cooling utilizing air or coolant. Eventually, the scope was narrowed down to focus on coolant-based cooling, a decision that was supported by the requirements outlined by Volvo Trucks. Among the different parts of the TVPDC, the connection ports are the key elements relevant to this thesis.

The scope was further widened to incorporate the investigation of the coolant, alternative materials for the busbars, and insulating material as opposed to the existing Thermal Insulating Material (TIM) to see their effect on the thermal performance of the busbars.

By analyzing the existing design and interaction with the engineers at Volvo Trucks, potential opportunities were found and focused on, with prioritization given to the cross-section of the busbars. The thermal simulation and heat dissipation were of utmost importance to this thesis. Consequently, the selected focal points of the thesis revolved around the cross-sections of the busbars and the cooling method, followed by the material selection for the busbars and the insulating material between the busbars and the TVPDC box.

1.5 Project Delimitation

The thesis spanned over 20 weeks. With the time frame in mind, the following choices were made in order to perform a detailed study to achieve the pre-determined goal of developing new cooling concepts for the busbar:

- In this thesis work, all conventional cooling methods using air and liquid were explored. However, due to narrowed goals and requirement lists, air cooling concepts were not explored in detail as they entail designing new supporting components for functioning.

- The total cost of the concept was approximated due to a need for more information on the manufacturing costs.

- The concept geometry was constrained by the initial geometry of the housing box for busbars.

- The thesis focused primarily on the cooling of busbars, and other factors, such as the coolant inlet temperature, were not explored.

- The concepts were developed and tested virtually in software such as Creo Parametric 8.0 and ANSYS Mechanical.

1.6 Research Questions

Based on the aim and objectives of the thesis work, the following three Research Questions(RQ) were formulated as stated below. The concept development and design methodology in the thesis work were mainly aimed at addressing and ultimately solving these questions :

- *RQ1:* How are the most optimal materials chosen for the coolant and the busbar regarding cost, performance, weight, and ease of replacement?

- *RQ2:* How can the maximum operating temperature of the busbar be reduced while being cooled simultaneously?
- *RQ3:* How can the busbars dimensions be optimized to increase the current flow efficiency with minimal heat generated?

1.7 Report Outline

The report begins with a concise introduction outlining the problem statement and research questions. The theory section provides readers with relevant background information, enabling them to understand the subsequent chapters. The methods used throughout the research are then highlighted in a subsequent chapter. Following the methods, the subsequent chapters delve into the different tools employed to aid in idea generation for the final concept starting from literature review to morphological matrix and eventually selecting the final concept using Pugh and Kesselring matrices.

The report concludes by presenting the final concept design in chapter six, which was carefully selected through a rigorous screening process and utilizing various tools discussed in the methodology chapter. A comprehensive comparison between the final concept and the existing design is provided to validate the obtained results and ensure transparency. Chapter Seven provides a concise discussion highlighting the essential tools and results obtained throughout the project. Finally, the report concludes with a summary of findings and recommendations for further research and development, emphasizing the need for Volvo Trucks to pursue additional in-depth investigations.

2
Theory

This chapter outlines battery electric vehicles and the components in focus for this thesis. Furthermore, it discussed the various heat equations and insight into finite element analysis with the supporting literature about trends in similar fields of work to conclude the chapter.

2.1 Battery Electric Vehicles

With the increase in CO_2 emissions, climate change, and the zealous interest of the population towards environmental issues, the importance of electric vehicles has rapidly increased in recent years. The emergence of battery electric vehicles (BEVs) is to combat future challenges caused by using fossil fuels and their by-products. In particular, with the service sector still relying on trucks for logistics, supply chain, and distribution, the field of electric trucks is vast to explore. It has been gaining popularity in development over the recent few years [6].

Any BEV, be it a car or a truck, primarily consists of primary components such as an energy storage system, a power inverter to convert the direct current(DC) generated from the batteries to alternating currents (AC), an electric motor to convert kinetic energy to mechanical energy thereby propelling the vehicle, a charging port to recharge the batteries and finally a battery thermal management systems (BTMS) to regulate the currents flowing to the batteries. Most BEVs also employ separate cooling systems to cool the batteries and other components. A BEVs' performance and driving range depends on the ESS and the number of battery modules used. The battery types also affect performance as they have different energy and power densities; for instance, lithium-ion batteries have superior energy density than lead-acid batteries [6].

BEVs are different from internal combustion (IC) vehicles in that they use electric motors to generate power as opposed to IC engines. However, on the flip side, BEVs are much heavier than IC vehicles due to the requirement of stacking many battery cells in a battery pack to generate the necessary power for the vehicle. Besides the benefit of no emissions, BEVs provide superior torque conversion, high efficiency, remarkable service life, and low maintenance and noise levels compared to IC engines [7] [8]. As the need for BEVs rises, the advantages will eventually outweigh its challenges and contribute towards sustainable development in transforming the world.

2.2 Components of TVPDC

Among various systems available in the BEV, the system or the assembly that is of interest to this thesis is the Traction Voltage Power Distribution Center(TVPDC). The TVPDC, also known as PDC or junction box, is the unit responsible for regulating current loads from the battery to other auxiliary ports depending on the usage of the connection ports. It uses the busbar interface to network all supporting units, such as the cooling system, electric motor drives, charging system, and other vehicles [9].

The primary benefit of having a TVPDC is the possibility of having one singular unit wherein all the electrical loads and supplies to other components can be managed and monitored easily for safety. The design of TVPDC is very flexible, depending on the requirements of the company developing its BEV. As such, each company has different connection ports available to the TVPDC.

There are many connection ports made available inside the TVPDC box. These ports are responsible for the current distribution from the battery back to respective units. The components' general descriptions and functionality inside a TVPDC junction box are discussed in the following sub-section. Fig 1 depicts the different components employed in a TVPDC box.

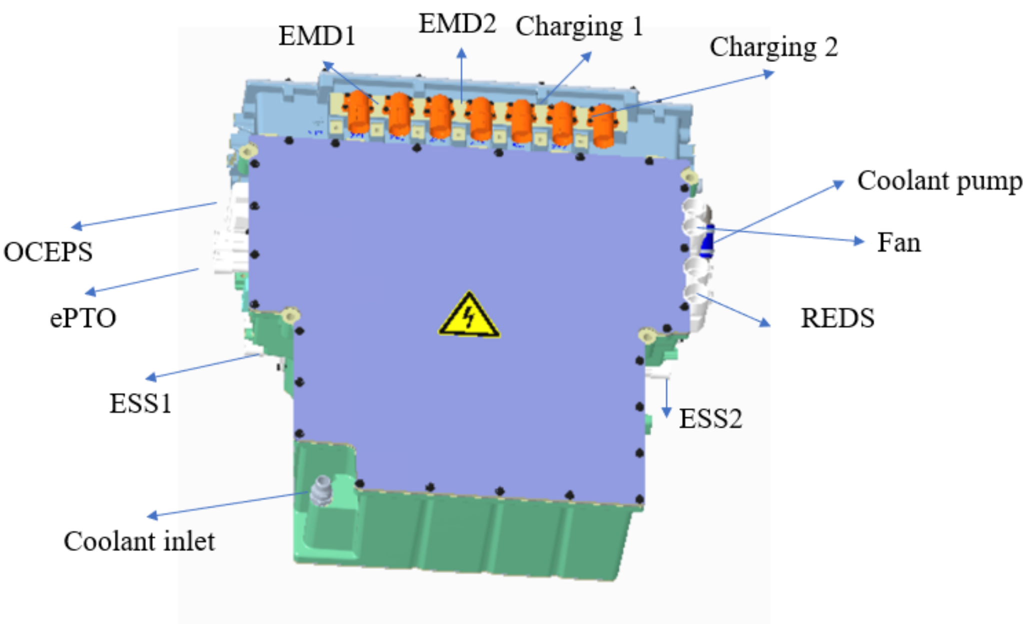

Figure 1: Components of TVPDC Box

2.2.1 Components Related to Connection Ports

EMD: Electric Motor Drive (EMD) is an electrical device that drives and controls the speed or torque in an electric motor. EMD converts the DC power generated from the battery pack into AC power for the motor to operate and eventually drive the BEV. Inside the TVPDC box, there are two EMD connection ports. Each of these ports contains two terminal connection ports, positive and negative, to complete the flow of current generated from the battery back. As trucks are heavier in general compared to cars and due to their general requirement of being able to haul massive loads, the two EMDs are typically placed in the rear wheel section of the vehicle to balance the center of gravity [9].

EMD converts the electrical energy generated from batteries to mechanical energy through electric motors. Most electric motors are placed in between the electrical supply and a drive. The EMD then regulates the power fed into the motor, which controls the speed, torque, and direction of current in an electric motor. EMD regulates the speed of the motor by changing the constant frequency and voltage inputs from the AC currents into variable frequency and voltage. The motor receives the right amount of power it needs by doing so. EMD also helps lower energy costs by providing the necessary power to the motor with less energy loss, leading to a smaller carbon footprint.

ESS: Energy Storage System (ESS) comprises one or several battery packs and a battery management function. In essence, ESS consists of multiple battery backs containing hundreds of battery cells (mostly Lithium-ion batteries, commercially used) that convert the electrical energy generated from these cells and store energy to supply this energy when needed. ESS assists in efficiently utilizing and controlling electrical energy, resulting in the added benefits of a stable electricity supply and reduced costs. The energy density of the ESS is dependent on the type of battery cells used and their cell geometries [9].

The number of connection ports inside a TVPDC box depends on the BEV manufacturers and space constraints. At Volvo Trucks, two ESS connection ports are placed inside the TVPDC box, each with a positive and negative terminal connection. ESS provides many advantages, such as peak saving, where most power is utilized during operation, and recharging the battery cells at night. However, a few challenges must be addressed when implementing an ESS in a BEV. The thermal runway is the biggest challenge most companies face when incorporating an ESS into their vehicle [9].

Fans: The fan has a single port inside the TVPDC with positive and negative terminal connection ports. The fan serves multiple purposes inside a BEV. It helps cool the battery system and pump the air into the cabin to keep the occupant warm or cold when necessary. Typically the vehicles require more current input to the fan when charging. Fans are required to effectively cool down the battery pack as battery cells generate heat when charged. The fan keeps the battery and the onboard component at optimal temperature for ideal charging rates [9].

OCEPS: Onboard Charger and Electric Power Supply(OCEPS) is a device that converts AC power from charging outlets in-home or at charging stations to DC power in order to charge the battery pack. The OCEPS interacts with the electric control unit and the charging station to determine the proper amount of current to be applied to the battery backs. It also has bi-direction functionality, which can convert DC power from the battery pack into AC power for other auxiliary components inside the cabin. The OCEPS has a single port inside the TVPDC with positive and negative terminal connection ports. OCEPS aims to control the current flow from the grid (charging outlets) to the traction battery [9].

REDS: The retardation Energy Dissipation System (REDS) is currently being developed at Volvo Trucks. The purpose of REDS is to dissipate the excess energy generated from the battery. Excess energy dissipation is achieved by utilizing the excess electrical energy and converting it into mechanical energy to power an auxiliary unit onboard the electric truck. The TVPDC employs a positive and negative connection terminal port for REDS [9].

ePTO: Electric Power Take-Off(PTO) is an interface that converts power generated from the battery. The ePTO takes input from the battery and works with the electric motor, hydraulic pumps, and a smart electronic control system to distribute the necessary power to auxiliary machines hitched to the electric trucks [9].
It comprises an inbuilt inverter to convert DC to AC currents and vice versa to supply power to auxiliary units. The current demands of the ePTO vary vastly depending on the auxiliary unit in use; for example, the cement mixer requires more power than hydraulic forklifts and garbage dumpsters. A single connection port exists for the ePTO inside the TVPDC box with two connection terminals, positive and negative ports.

CCS: A combined Charging System (CCS) is a commercially used charging-plug system that enables charging using AC or DC power. CCS builds upon the Type 2 connector mostly employed by EVs to charge. It comprises two additional DC power lines to run at a higher voltage instead of standard charging connectors. CCS thereby reduces the charging speed time. It has a converter embedded into its design, making converting power from DC to AC much easier. The TVPDC employs a single connection port for CCS with two terminal attachment points to distribute power from the grid to the ESS [9].

MCS: Megawatt Charging System (MCS) is a high-power charging connector currently under development for BEVs. The MCS is a modular solution and comprises an electronic module, MCS connector, and inlet that serves as a mating device with charging station ports. It significantly reduces the charging time and maximizes up-time compared to the existing CCS. The TVPDC employs a single connection port for MCS with two terminal attachment points to distribute power from the grid to the ESS. A global company, Charin, is developing a megawatt charging system with an electrical rating of 3.75MW. MCS is expected to reduce the climate impact more than existing CCS [10].

2.2.2 Other Components

PCB: A printed Circuit Board(PCB) connects electrical components, typically using metallic paths etched on a non-conducting substrate (board). They provide mechanical support for electronic components to mount a device in an enclosure. The insulating material is sandwiched between conductive layers to form the mechanical structure. It is coated with a non-conductive solder mask and labeled with a silkscreen legend for electronic components [9].

Fuses: The TVPDC box incorporates multiple fuses to safeguard the interior components, including the PCB. It also includes circuit breakers to protect all systems when high currents flow through them. The use of electric fuses helps prevent hazards such as high temperatures, power surges, current overload, and short circuits from affecting the electrical systems. As EVs are subjected to harsher loads such as vibration and high currents, the fuses used in EVs are designed to withstand more vibration and faster circuit breaking while also coping with thermal stresses and current fluctuations [9].

Busbar: Busbars are solid conductors utilized to transmit current from one location to another within an EV. While cables are typically the standard and safest method of transmitting current, EVs require larger-diameter cables to adequately handle the high current demands. This need for increased cross-sections to carry sufficient current makes cables more space-consuming and challenging to manage during assembly. As a result, busbars are the preferred alternative in EVs [11].

TIM: Thermal Interface Material (TIM) dissipates and enhances heat transfer in busbars within the TVPDC box. TIM can be in the form of thermal conductive sheets or conductive adhesives. At Volvo Trucks, TIM is used as thermal sheets placed underneath the busbar assembly to dissipate heat generated by high currents in the busbars efficiently.

Housing: The housing of the TVPDC box encompasses all its components. It provides structural support and enclosure for all electrical components and connections. Additionally, it protects electrical connections from harsh weather conditions and offers insulation to prevent electrical shocks when servicing the vehicle.

Cooling System: The cooling system serves the purpose of cooling down the busbars. They are placed underneath the TIM material on a metal sheet containing pathways for the coolant to flow from the pump inlet and exist through an outlet that is diverted to a reservoir and then back to the inlet. The number of cooling channels influences the cooling efficiency, but more channels require additional space and power from the pump.

2.3 Busbars

As mentioned previously, busbars are solid metal bars utilized for conducting current. Typically made from copper or aluminum, they differ from cables in that they are rigid, flat, and have a shorter height, up to 70 percent shorter. Despite their reduced height, busbars can carry more current than cables with the same cross-sectional area. These characteristics make busbars ideal for specific high-voltage connections in electric vehicles (EVs) and an essential component of upcoming vehicle electrical designs [4] [11].

In an EV, the busbars function similarly to the blood vessels in our bodies. They serve as significant electrical pathways, facilitating the transmission of electrical current throughout the various systems and sub-systems of the vehicle, much like how blood vessels transport blood throughout the body. While the battery is commonly considered the heart of the vehicle, the busbars play a crucial role in ensuring efficient and effective distribution of electrical power.

2.3.1 Types of Busbars

Busbars are typically made from copper or aluminum and have more electrical conductivity due to their larger surface area. However, not all busbars are solid, stiff conductors. Different busbars are utilized to fulfill the intended use of the part. The following are the different types of busbars predominantly used in the EV sector.

Solid Busbars: These are convectional solid conductors made from copper or aluminum. They offer all the advantages of the busbar listed in the below sub-section. Traditionally, the name busbars is associated with solid busbars. They are often stamped to a solid bar and then machined to desired shape. However, in doing so, the machining costs increase. In recent years most OEMs have been leaning towards using progressive die stamping according to the desired geometry. These busbars are often coated with tin, silver, or nickel to increase the electrical conductivity while at the same time offering corrosion resistance and the formation of copper oxide.

Flexible Busbars: As the name implies, flexible busbars are designed to be flexible, unlike solid busbars. They are created by combining multiple layers of copper or aluminum. The most common design of flexible busbars consists of tightly diffusion-welded layers of copper foil at the mounting areas. This design allows the ends of the busbars to be rigid while maintaining flexibility in the middle section. Flexible busbars offer easier installation as they can be curved, twisted, and bent to fit into tight spaces. They are usually protected by a polyvinyl chloride (PVC) jacket for electrical insulation during assembly. With a larger surface area, flexible busbars provide increased electrical conductivity and shock resistance compared to solid busbars.

Laminar Busbars: Laminar busbars share similarities with flexible busbars as they are also multi-layered. They consist of multiple layers of conductive metals (copper or aluminum) separated by thin layers of dielectric material. These layers are integrated into a single component through a heating and compression process. Laminar busbars can be manufactured in various forms, such as strips, tubes, or solid bars. The critical difference between laminar and flexible busbars lies in their structural characteristics. Laminar busbars offer greater sturdiness and rigidity, generating lower heat and exhibiting the lowest inductance among all busbar types.

2.3.2 Advantages of Busbar

The following points list the significant advantages of busbars over cables and the reason for their increased demand in the EV sector.

- ***Compact Design:*** Busbars allow for a more compact design than cables, as the cross-section of cables needs to be larger to match the current density of busbars.

- ***Reduced System Costs:*** Busbars are easier to manufacture than cables, as they are solid components as opposed to drawn-out thin layers of copper material. Also, busbars are much easier to manage and reduce assembly time, material handling, and inventory costs.

- ***Greater Flexibility:*** Busbars are much more flexible in design and are more modular than cables. They are easy to customize and modify for BEV manufacturers to fit into any additional space. The addition, reconfiguration, or replacement of the busbars can be carried out with minimal disruption to the supporting systems.

- ***Lower Inductance:*** Busbars have lower inductance than cables, allowing for higher current density. The minimal distance between the attachment of two or more busbars results in lower resistance and voltage drop compared to cables.

- ***Efficient Heat Dissipation:*** Busbars have a larger surface area as opposed to cables, enabling efficient heat dissipation as more surface area is exposed to ambient temperatures.

- ***Improved Rigidity:*** Busbars exhibit greater structural integrity than cables, allowing them to handle higher structural loads and provide stability against vibrations.

2.3.3 Challenges of Busbars

Busbars are the perfect alternatives for cables in EVs. However, implementing busbars in BEVs is often more complex than one might think; a few challenges must be addressed when using busbars. The following major challenges must be addressed before implementing busbars [12].

- ***Heating:***Busbars, being solid conductors, generate more heat compared to cables. Therefore, it is crucial to design efficient cooling systems to effectively reduce busbars' operating temperature.

- ***Electrical Insulation :*** In areas where busbars are exposed for easier servicing and assembly, proper electrical insulation is essential. Busbars carry higher current density than cables, necessitating more stringent insulation requirements to ensure safety. Any insulation failure could have catastrophic consequences for both the electric vehicle and its occupants.

- ***Proper Attachment:*** Busbars are typically attached using bolts, clamps, or welding. Necessary care and precaution must be taken during the mounting process. Improper bolting, clamping, or welding can increase electrical resistance at the attachment points, leading to additional heating of the busbars.

2.4 Cooling Methods

As previously mentioned, one of the primary challenges associated with busbars is overheating and the necessity for effective heat dissipation. In response to this issue, numerous battery electric vehicle (BEV) manufacturers are researching efficient cooling methods that ensure optimal cooling for busbars without compromising the component's structural integrity. Cooling systems for busbars typically employ either air or liquid cooling, with water and glycol mix being a common choice for coolant. The following subsection discusses the various cooling methods employed for busbars.

2.4.1 Indirect Cooling

In the indirect cooling method, there is no direct surface-to-surface contact between the cooling medium (air or water) and the object to be cooled. This approach simplifies the design of additional supporting units, making it easier to integrate into existing vehicle architectures. The effectiveness and complexity of the indirect cooling method can vary depending on the cooling medium utilized.

Indirect cooling using air uses a heat exchanger to dissipate the heat generated in the conducting component. The heated air is discharged outside the system, while the cooled secondary medium is circulated back to the component to absorb more heat. This process ensures a constant temperature gradient and facilitates heat dissipation from the conducting component. Numerous applications, such as data centers, industrial processes, and HVAC systems, frequently use indirect air cooling. Indirect air cooling offers benefits such as improved energy efficiency, reduced environmental impact, and protection of delicate equipment from direct contact with potentially contaminated or humid ambient air [13].

In an indirect liquid cooling system, a liquid coolant, such as water or a specialized coolant, circulates through a heat exchanger or cooling plate, directly interacting with the heat-generating components. The liquid absorbs heat from the components, carries it to the heat exchanger, and then transfers it to the surrounding air.

Indirect liquid cooling provides a higher heat transfer efficiency compared to air cooling due to the greater heat capacity and thermal conductivity of liquids. However, implementing indirect liquid cooling requires additional infrastructure, such as pumps, radiators, and a coolant distribution system, making it more challenging and potentially more expensive than traditional air cooling techniques.

2.4.2 Direct Cooling

As the name implies, there is direct surface-to-surface contact between the conducting surface and the cooling medium in the direct cooling method. Direct cooling employs air or liquid as a cooling medium, like indirect cooling. Direct cooling using air as a cooling medium involves fans circulating air directly over a heat source or equipment to remove heat and cool it down. Typical applications for this technique include computer cooling, electronics cooling, and some industrial operations. Direct cooling using liquid involves either the passage of liquid coolant through the geometry of the conducting part or by immersing the whole part in the coolant.

Direct cooling represents a notable advantage over indirect cooling methods, especially in the EV sector. Electric motors' electrical losses occur due to the current flowing through the copper windings, which offer low resistance. These losses increase proportionally with the current, resulting in elevated heat levels within the motor. Magnetic losses further contribute to heat generation in the stator and the rotor. Direct cooling addresses this heat at its source, within the windings themselves, rather than relying solely on cooling mechanisms applied to the motor housing [13].

The higher efficiency achieved through direct cooling in electric vehicles (EVs) brings forth a multitude of practical implications. Firstly, it enables the design of smaller and lighter power units. With direct cooling, the heat generated by the electric motor can be efficiently dissipated, reducing the size and weight of the cooling system required. This reduction in size and weight not only improves the overall performance and maneuverability of the vehicle but also contributes to significant weight reduction and cost savings. Direct-cooled motors can utilize standard and cost-effective materials, including inexpensive magnets, resulting in higher performance at a more affordable price point. These factors are pivotal in driving the broader adoption of electric vehicles [14][15].

The thesis revolves around the exploration of direct cooling methods extensively, while indirect cooling using liquid was also taken into consideration in the idea generation phase. The final concept employs direct liquid cooling due to its superior performance and heat dissipation than the indirect cooling method.

2.5 Heat Transfer Principle

Heat transfer theory involves three modes of heat dissipation: convection, conduction, and radiation. In the case of a closed system TVPDC box, the entire space is designed to be waterproof, considering only the static conduction situation. Additionally, the radiation emissivity of the copper busbar surface is relatively low, with a value of 0.2 [16]. Therefore, heat dissipation through radiation can be neglected.

Heat Convection in a static air flow situation can be simplified. The heat convection equation considers the air convection coefficient(H), the contact surface area(A), and the temperature difference between the busbar and the air, as shown in equation (2.1).

$$\dot{Q} = H \cdot (T_{\text{busbar}} - T_{\text{air}}) \cdot A \tag{2.1}$$

Heat Conduction depends on four factors: the material conductivity (k), the thickness of the heat transfer path (L), the contact surface area (A), and the temperature difference between the two materials. Equation (2.2) represents the heat conduction equation.

$$\dot{Q} = \frac{k}{L} \cdot (T_{\text{busbar}} - T_{\text{air}}) \cdot A \tag{2.2}$$

2.6 Finite Element Method Simulations

- ***Joule Heating:*** When an electric current passes through a conductor, resistive losses occur, generating heat. The resistivity of the material and the current density distribution are considered as shown in equation 2.3

$$Q = I^2 \cdot R \tag{2.3}$$

- ***Thermal Conductivity:*** Heat is conducted within the busbar material due to temperature gradients. ANSYS considers the thermal conductivity properties of the material to model heat transfer accurately.

- ***Convection and Radiation:*** In addition to conduction, heat can be dissipated through convection (transfer of heat between a solid surface and a fluid) and radiation (emission of thermal radiation from a surface). ANSYS allows the inclusion of convection and radiation boundary conditions to simulate these heat transfer processes. However, as mentioned earlier, this thesis does not use radiation conditions.

- ***Material Properties:*** The thermal-electric module in ANSYS allows the user to specify the relevant material properties, such as electrical conductivity, thermal conductivity, specific heat capacity, and temperature-dependent properties. In this project, copper silicon rubber and coolant are considered.

- ***Meshing and Solution:*** ANSYS employs a finite element meshing technique to discretize the busbar geometry. The software then solves the coupled electric and thermal equations iteratively to determine the temperature distribution.

2.6.1 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) is a field of study that employs numerical methods and algorithms to simulate and analyze fluid flow and heat transfer. CFD is used to model convection and other fluid-related phenomena, which play a significant role in determining the pressure distribution of the coolant tube in this project. Pressure drop is the final output of the CFD simulation. By incorporating both FEM and CFD techniques, the simulation of the temperature distribution in copper busbars is enhanced, accounting for electrical and thermal properties and fluid dynamics of the coolant.

2.7 Trends in Industry

The efficient cooling of busbars is crucial in high-power applications, particularly in scenarios where there is a need for rapid heat dissipation. One innovative solution to address this requirement is the utilization of hollow busbars. These busbars draw inspiration from a mature product called hollow conductors. Two main applications of hollow busbars are air cooling for high-voltage, high-power, and high-density transmission systems and direct liquid cooling for motor stator cooling [17][18].

In high-voltage power transmission systems, where large currents and high power densities are involved, hollow busbars have been developed, featuring an internal hollow structure that allows the passage of compressed air for cooling. This innovative design enables rapid heat transfer, ensuring the busbars can operate within acceptable temperature limits even under demanding conditions.

Another advanced application of hollow conductors is their integration into the stator windings of electric motors for direct liquid cooling. By winding thin and elongated hollow conductors within the motor's stator, it becomes possible to circulate a cooling liquid directly through the conductors. This approach maximizes heat removal from the motor's stator, enhancing cooling efficiency and overall performance [19] [20]. The concept of hollow conductors finds extensive application in the cooling of electric motors, particularly in the context of electric vehicles (EVs). Luvata, a renowned company in the field, leverages hollow conductors to introduce new possibilities for motor cooling, enabling significant performance enhancements [21].

The exploration of cooling techniques used in BEVs and understanding of industry trends provided valuable insights for the thesis development. This investigation established a solid knowledge foundation, offering essential guidance for advancing the thesis project and contributing to the field of cooling busbars.

3

Methodology

This chapter provides insight into the methodology and different tools employed across different stages in the thesis work. The chapter also briefly introduces these tools and their purpose in this thesis.

3.1 Methodology Overview

In order to envision and capture the entire scope of the thesis work, a structured traditional product development method is employed. The process encompasses five stages, from requirement identification to concept generation, followed by concept selection, testing, and evaluation [22].

The structured method was followed as it eliminates uncertainty and leads to innovative solutions. Also, an iterative process between stages was employed to ensure the credibility and incorporation of new ideas throughout the development process, as shown in Fig. 2. The iterative approach ensured that no concept was selected or eliminated in the initial stages without adequate knowledge concerning the solution space.

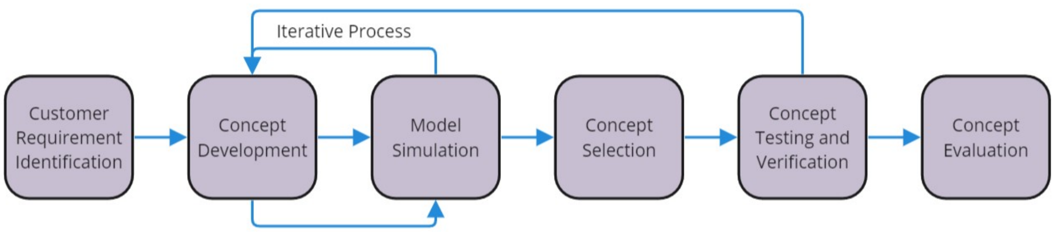

Figure 2: Methodology Flow Chart

Table 1 lists out different tools employed at each stage of product development in the thesis.

Table 1: Methodology Tools Employed

Product Development Stages in Thesis	Tools Employed
Customer requirement identification	Requirement List
Concept Development	Black box model Process flow
	Function means tree Brainstorming TRIZ
	Material Study Idea Generation matrix Morphological matrix
Model Simulation	Thermal- Electric using ANSYS CFD using ANSYS
Concept Selection	Elimination matrix Pugh matrix
Concept Verification and Testing	Simulation of model Prototyping of concept
Concept Evaluation	Kesselring matrix Fulfillment of requirements

3.2 Literature Study

In order to establish a solid foundation for the thesis work and identify the project's requirements, it was essential first to understand the scope of the research and potential solutions. This was achieved through a comprehensive literature review, which provided valuable insights into the nature of busbars, their role in electric vehicles (EVs), and possible approaches to address the project's aims and objectives. The literature search involved exploring scientific journals from portals such as Science Direct, IEEE, and ResearchGate and utilizing the Volvo intranet portal to understand relevant acronyms and the interrelationships between different aspects of the design scope. Furthermore, scientific studies on the effects of different solutions and mathematical equations related to heat were examined to generate concrete and innovative solutions.

During the initial literature search, particular attention was given to patents and conference papers, which inspired potential solutions to address overheating busbars. Tesla's patent on direct liquid cooling of busbars served as a catalyst for envisioning this approach [23], while ABB's technology patent inspired the idea of utilizing heat pipes for busbar cooling [24]. Additionally, alternative materials such as copper-clad aluminum were discovered and extensively investigated as potential options for busbar construction [25]. The optimization of busbar design was also explored as a potential avenue for enhancing heat dissipation [26].

3.3 Functional Analysis

The functional analysis of the busbar cooling system was implemented using methods such as the black box model, process flow, and function means tree. Each of these methods aided in the comprehension and functional decomposition of the cooling system. The main functions were identified and further broken down into appropriate sub-functions to map diverse ideas using a morphological matrix for idea generation [22]. The purpose of following a structured functional analysis in this thesis was to properly document all ideas while ensuring that knowledge and probable challenges faced between the interaction of parts were thought of in the first place before concept development.

The black box model helped discern all inputs and outputs of the busbar cooling system to the environment. The inputs served as the primary factors in determining the requirement specification, while the outputs assisted in testing the overall efficiency of the concept design. The process flow model was constructed to comprehend the overall process of busbar cooling. In doing so, many complex functions were broken down into various sub-functions to generate vast ideas. The functional means tree bridged the gap between theory and concept by identifying several sub-functions and their associated means. This method made the process of idea generation much easier and more structured. The end output of all the functional analysis methods was to form an array of ideas through which concepts could be created by mismatching these ideas using matrices.

3.4 Material Study

A material study was conducted using systematic methods, as mentioned in the following subsections. Material study aided in the identification of material alternatives or the justification of the existing material.

3.4.1 Material Benchmarking

The material benchmarking was done through a comprehensive interview with Volvo Supervisor, a literature study, and material property comparison using CES Educpack. Material benchmarking aimed to explore the possibility of using an alternative material for the busbar. The material benchmarking was conducted to investigate the competitor's material choice to aid in the final selection of the chosen concept while analyzing possible trade-offs such as cost, weight, and efficiency.

3.4.2 Material Selection

The benchmarked material was compared against material alternatives, with the selection criteria being the material properties of importance listed in the requirement specification. The material properties of interest to this project were the strength-to-weight ratio and thermal and electrical conductivity. While the cost of material was considered, it was not the primary selection as the requirement of the thesis prioritized efficiency over cost. The potential material alternatives were then selected for design and simulation comparison against the existing busbar material being used at Volvo Trucks.

3.5 Idea Generation

The implementation of idea-generation methods facilitated the generation of various ideas for creating new concepts for cooling busbars. Each method, such as brainstorming, TRIZ, and morphological matrix, yielded diverse ideas for the sub-functions identified using functional analysis methods.

3.5.1 Brainstorming

The most traditional method employed in idea generation is brainstorming. Brainstorming helped in generating ideas that were combined to form a concept. The brainstorming activity was carried out in a group comprising Volvo engineers to learn different approaches to a problem addressed by each sub-function. The brainstorming sessions involved pictorial representations and simple CAD modeling in helping other team members understand easily while also painting a visual picture of the idea in mind.

3.5.2 TRIZ

The TRIZ method was explored to investigate problem-solving approaches in different industries to implement in the current problem. TRIZ method was carried out by describing the problem statement and solution alternatives from other sectors as inspiration for a new idea or the possibility of using the same solution in the thesis. The outcome of the TRIZ method resulted in new concept ideas. However, these ideas were not explored further upon discussion with the Volvo team and revisiting the requirement list.

3.5.3 Morphological Matrix

The morphological matrix employed functional analysis and incorporated various sub-solution ideas from the brainstorming matrix to generate innovative concepts. By combining various sub-solutions for each sub-function, the morphological matrix facilitated the creation of a diverse range of conceptual designs. Although the number of output concepts from the matrix was limited, a systematic approach was followed to thoroughly consider all possible combinations of sub-solutions within the project's scope. This structured method guaranteed that every possible combination aligned with the project's objectives was carefully examined and evaluated. By adhering to this systematic process, the morphological matrix enabled a comprehensive exploration of potential design configurations.

3.6 Concept Selection and Evaluation

Concept selection and evaluation methods were employed to refine the concepts generated through a morphological matrix. Concept selection aimed to choose ideas that aligned with the project scope, while concept evaluation ensured that the final concepts met the pre-defined requirement specifications.

3.6.1 Elimination Matrix

An elimination matrix was utilized to assess and evaluate the chosen concepts of a product against pre-set criteria of product requirements by customers, safety, cost, compatibility, and project scope. The matrix gave an idea as to whether enough information was present to proceed with the concept or if additional research was required to look at the concept's viability [22] .

The symbols; *'+', '-'* and *'?'* corresponding to *yes, no,* and *not enough information* respectively, were used. This was done to examine each concept against each evaluation criterion and determine the possibility of further development for each concept [27].

3.6.2 Pugh Matrix

The Pugh matrix was employed to compare the various concepts against each other, facilitating the identification of potential advantages one concept held over another. This method involved selecting a baseline concept and assigning the remaining concepts a grade of +, -, or 0, indicating an advantage, a disadvantage, or neutrality regarding specific sub-functions, respectively [22]. Multiple iterations of this process were carried out until the results achieved convergence.

3.6.3 Kesselring Matrix

The Kesselring matrix was used to evaluate the optimal concept among the remaining concepts in the Pugh matrix. This matrix involved quantifying all desires and requirements on a measurable scale ranging from 1 to 5, with values assigned based on engineering assumptions and prior knowledge of the requirements. Each desire was then assigned a proportional significance, ensuring that the total weight of all desires equaled 100%. The concepts were subsequently ranked according to their cumulative weight, and the best concept was selected as the final choice [22].

3.7 Simulation Driven Designs

With the final concepts being narrowed down using the Kesselring matrix, FEM simulations were conducted to compare the results with the existing design. Thermal-electric and CFD simulations were carried out. The simulations helped drive the concept design into a fully functional model. Several iterations and changes were made to the final concepts based on simulation results, with even new concept inspirations emerging during the process. Thermal-electric simulation aided in reporting the maximum operating temperature of the design under a pre-set environment, and the CFD simulation gauged the acceptable pressure drop for the design.

4
Pre-Study

This chapter dives into the work carried out prior to concept development. The chapter identifies key requirements and their translation into functions through functional analysis tools. A detailed material study is also entailed in this chapter.

4.1 Requirement Specification

The requirement specification list provided a stable base and metric during concept generation, evaluation, and verification of the final concept. The thesis explores the possibility of efficiently cooling down busbars that carry high currents in the range of 500 A or more. As such, priority is given to the concept's safety while ensuring that it provides superior heat dissipation compared to the existing design. The data and focus of requirements were collected using data collection methods such as targeted interviews, literature study, and engineering knowledge. The prioritization and relevant importance of each requirement based on customer needs is depicted in Table 2.

Table 2: Customer Needs List

S.No	Requirement	Importance
1	Reduce the maximum temperature of the busbar	High
2	The system has geometry within the dimensions of the TVPDC box	Low
3	Inexpensive system solution	Medium
4	A simple and effective system	High
5	Easy to manufacture	Medium
6	Sustainable solution	Medium
7	Lightweight design solution	High

The requirement specification list presented in Appendix A was developed considering the objectives of the thesis work and the specific requirements of Volvo Trucks. In addition to the mandatory requirements, the thesis team incorporated a few desires into the list to enhance the complexity and comprehensiveness of the solution to be developed. The list was organized into seven main categories, including safety, manufacturing, geometry, weight, maintainability, and sustainability criteria. Each category was further divided into sub-criteria to facilitate understanding and provide transparency regarding all requirements and desires. The requirements within these criteria were specified as target values or statements, and their verification was carried out through various means such as CAD (Creo Parametric) modeling, simulation (ANSYS), CES Educpack analysis, and prototyping. These verification methods ensured that the requirements were effectively addressed and met in the final concept design.

4.2 Black Box Diagram

The black box model is a method used for the functional decomposition of a system, which defines the relationship between inputs and outputs without revealing internal workings [28]. In this thesis, busbars' cooling concepts are considered a system with multiple inputs and outputs. The purpose of employing the black box model is to perceive the various input variables that impact the overall temperature increase of the busbars during operation.

The inputs for the cooling concepts include mechanical load and vibration on the busbars, thermal and electrical loads on each busbar, coolant variables such as the number of cooling channels, the ambient temperature of the coolant, the type of coolant, and the effect of environmental temperature on the cooling structure. With the inputs taken into account, the outputs aim to address the initial objectives of the thesis work, which involve effective heat dissipation across a wider range of environmental temperatures. Consequently, the cooling concept provides efficient and safe cooling for the busbars, resulting in an elevated maximum operating temperature and enhanced current capacity. Figure 3 illustrates the black box model.

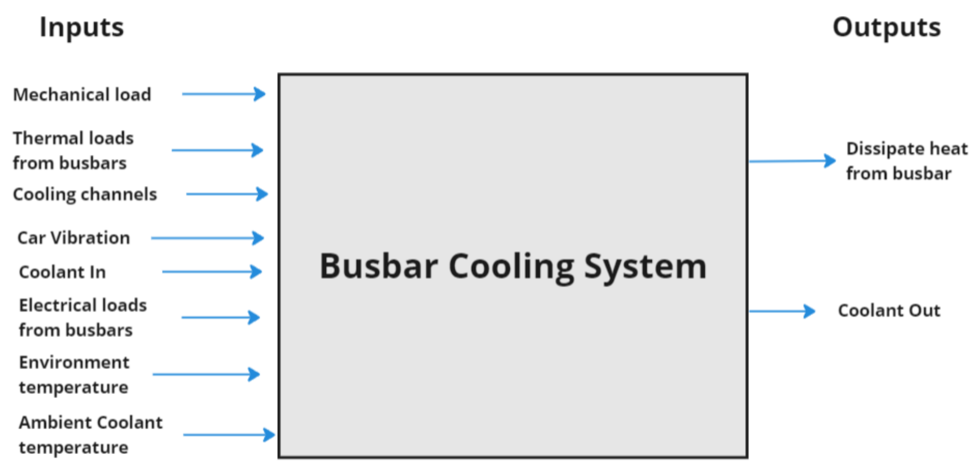

Figure 3: Black Box Model for Busbar Cooling System

4.3 Process Flow

The process flow model is a method used to understand the sequential steps and key considerations involved in a process [22]. In the context of cooling busbars, the process flow chart was employed to identify different sub-functions and analyze the sequential flow of these functions. Several process flow charts were created using different operands, referred to as process characteristics, as no material transformation was involved. One flow chart focused on the cooling method and efficiency, with the input operand as "overheating busbar" and the output operand as "cool busbar." This chart highlighted the cooling process and its effectiveness rather than the supporting activities. Another flow chart emphasized safety improvements, with the input operand as "Unsafe cooling" and the output operand as "safe cooling." This chart aimed to enhance actions related to safety while cooling the busbar. While the sub-functions were determined through interviews, literature study, and engineering knowledge, establishing their sequence posed a challenge.

Considering these difficulties, a process flow chart was created to depict the actual flow of current through the busbars, leading to their heating. This flowchart, shown in Figure 4, focused on actions contributing to busbar heating rather than the actions involved in busbar cooling. This allowed for a comparison between different flow charts and facilitated the identification of links between sub-functions necessary to enhance either safety or efficiency in relation to the cooling process. While the black box model helped identify the inputs and outputs of the busbars regarding their surroundings, the process flow model assisted in identifying the specific sub-functions involved in cooling the busbars.

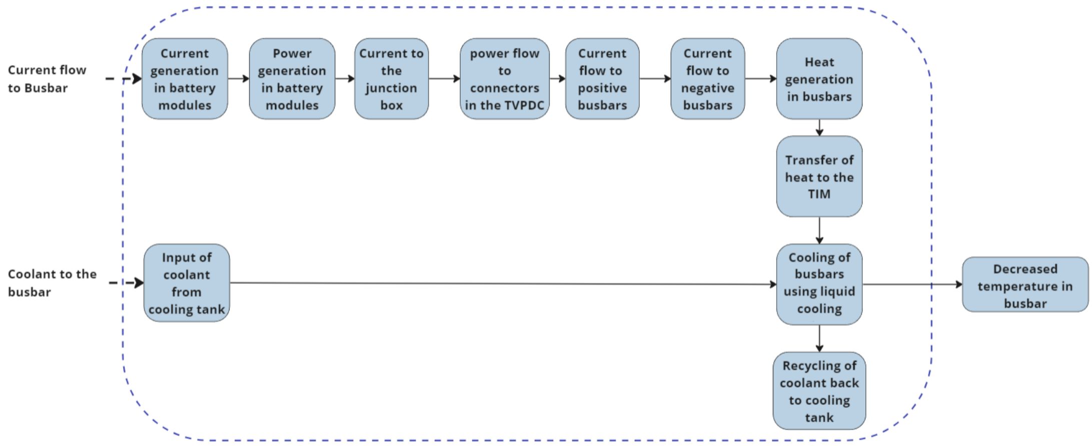

Figure 4: Process Flow for Busbar Cooling System

4.4 Function Means Tree

After analyzing the process flow chart and understanding the sub-functions involved, a function means tree was explored. The function means tree aims to map the relationship between the main function and its corresponding sub-solutions or means [22]. The goal was to identify multiple sub-solutions that could fulfill the primary function.

Following the identification of sub-solutions, a decision-making step was employed to select the best sub-solution. A lower level of the hierarchy was then used to define the necessary sub-functions for that chosen sub-solution, and the process was repeated for those sub-functions. However, in this stage of the thesis work, not all possible means for the identified functions were considered, as it would limit the number of sub-solutions for a specific function. This approach resulted in unreliable outcomes; therefore, the subsequent technique would replace it to improve the results.

4.5 Function Tree

To overcome the decision-making challenges faced by the function means tree method, the functional tree method was employed. The functional tree method aimed to identify the primary function related to the overall working principle of the design, specifically the cooling of the busbars. This approach involved breaking down the primary function into lower-level sub-functions to achieve the highest level of detail possible [22].

By consolidating the outcomes of the three process flow charts, it became apparent that certain sub-functions from different flow charts had strong relationships with each other. These relationships facilitated the grouping of sub-functions at the lowest hierarchy in the function tree. For example, in Figure 5, the sub-sub functions "mount components" and "enable servicing" were grouped under the sub-function "operation facilitation." It is worth noting that "enable servicing" was primarily focused on maintainability and was not initially part of the busbar process flow chart. However, it presented a compelling argument regarding the accessibility and ease of replacing components in the busbar cooling concept, particularly in the case of failure or manufacturing defects.

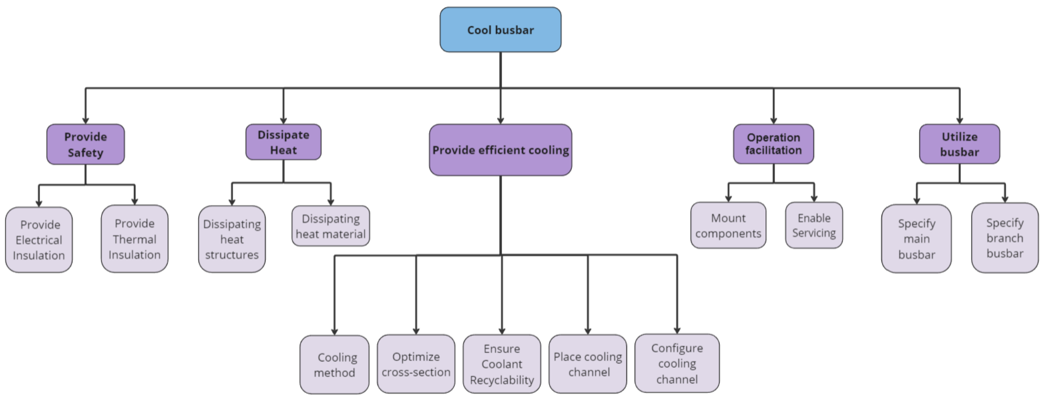

Figure 5: Function Tree for Busbar Cooling System

The 13 functions at the lowest hierarchy of the functional analysis are discussed briefly below.

1. Provide Electrical Insulation: This function refers to ideas about different possible ways to provide electrical insulation to the busbar and the coolant channel. This function aims at the safety aspect of the design and prevents unfortunate accidents during operation or installation.

2. Provide Thermal Insulation: This function refers to solutions by which the coolant channel is thermally insulated. This function ensures that the heat is dissipated efficiently from the coolant channel while ensuring the coolant's ambient temperature does not increase significantly.

3. Dissipating Heat Structures: This function lists various types of heat-dissipating geometry profiles and supporting modules paired with busbars to aid in effective heat dissipation. This function comprised geometry modification to the busbar, such as adding fins and holes and incorporating busbars with heat sinks.

4. Dissipating Heat Material: This function explores different material possibilities that improve the busbar's heat dissipation characteristics. This function, in essence, seeks out possible material alternatives for busbars.

5. Cooling Method: This function pertains to different cooling methods feasible with busbars.

6. Optimize Cross-section: This function lists all possible geometry cross-sections to a busbar. This function was explored to identify the dependence of the cross-section and temperature rise when a coolant is used in a busbar.

7. Ensure Coolant Recyclability : This function refers to all solutions that ensure that the coolant is recycled within the BEV, with minimum maintenance requirements and human intervention.

8. Place Cooling Channel: This function refers to all ideas pertaining to the placement of the cooling channel with respect to the TVPDC junction box.

9. Configure Cooling Channel: This function describes the number of cooling channels employed. This function was investigated to understand the correlations between the number of cooling channels and the rate of temperature decrease in busbars.

10. Mount Components: This function elucidates the various ideas employed to mount two different components; for instance, between the laminar and flexible busbar or between the busbar and the cooling channel.

11. Enable Servicing: This function refers to different ideas that facilitate ease of servicing in the overall design. This function also aims at the accessibility and replacement of components.

12. Specify Main Busbar: This function refers to the type of main busbars employed. The main busbar is a single or group of multiple busbars that bridge the gap and carry current from connection ports to the desired location.

13. Specify Branch Busbar: This function refers to the type of branch busbars employed. The branch busbars receive current directly from the connection ports such as OCEPS, ESS, and CCS.

4.6 Materials Study

A thorough materials study was conducted to analyze the influence of material properties on the thermal and electrical behavior of the busbar. This study explored alternative materials for the busbar, considering their impact on the overall performance. The selection process aided in selecting new material or in the justification of the existing material. Furthermore, the environmental impact of the new materials was carefully examined, considering factors such as sustainability and ecological considerations. This analysis aimed to strike a balance between optimal performance and minimizing the ecological footprint of the busbar design.

4.6.1 Material Benchmarking

The material information for the busbars was collected from various sources, including research institutes, the ASM Handbook, BEV benchmarking data, and the CES Edupack software. These sources provided valuable data on different materials and their relevant properties. Primary sources such as interviews, literature reviews, and knowledge transfer sessions were also conducted to gather insights and expert opinions on suitable materials for busbars. The information gathered from these sources was organized and analyzed in an Excel sheet, which facilitated the comparison of different material options based on their properties. The existing material used for the busbars initially served as a reference benchmark. However, exploring beyond this material and considering other possibilities was important. The thermal conductivity of the materials emerged as a critical property for busbar performance in the context of this thesis. It played a significant role in the final material selection process, but the existing busbar material remained an essential benchmark for comparison.

4.6.2 Material Selection

The material selection process aimed to identify new materials that could enhance the heat dissipation rate of busbars while maintaining good electrical conductivity. Several material properties were considered crucial in this study, including thermal conductivity, electrical resistivity, cost, CO_2 emissions during material production, and tensile strength. In order to explore a wide range of material choices, the initial approach excluded the benchmark material. This allowed for a comprehensive examination of alternative options. Since the busbars' function requires high electrical conductivity, the focus was primarily on metals and their alloys. The initial exploration did not consider plastic, non-ceramic materials, and honeycomb structures due to their limited suitability for high electrical density applications.

The material selection process utilized CES Edupack software to evaluate and eliminate materials based on specific criteria systematically. The process involved multiple elimination stages in narrowing the choices and identifying materials aligned with the thesis objectives. In the first stage, the limiting criterion was set as a minimum target value of 100 W/mK for thermal conductivity. This criterion aimed to ensure that the selected materials could effectively dissipate heat. As a result, the initial pool of materials was four hundred material choices.

The second stage focused on the price of materials, with a maximum value of 100 SEK/kg. This criterion aimed to consider the cost-effectiveness of the materials. The evaluation based on price further reduced the number of materials to two hundred and eighty. The final elimination stage incorporated two sustainability-related criteria: recyclability and primary production CO_2 emission. The objective was to prioritize environmentally friendly materials with low emissions. The target value for recyclability and primary production CO_2 emission was set at 10 kg/kg.

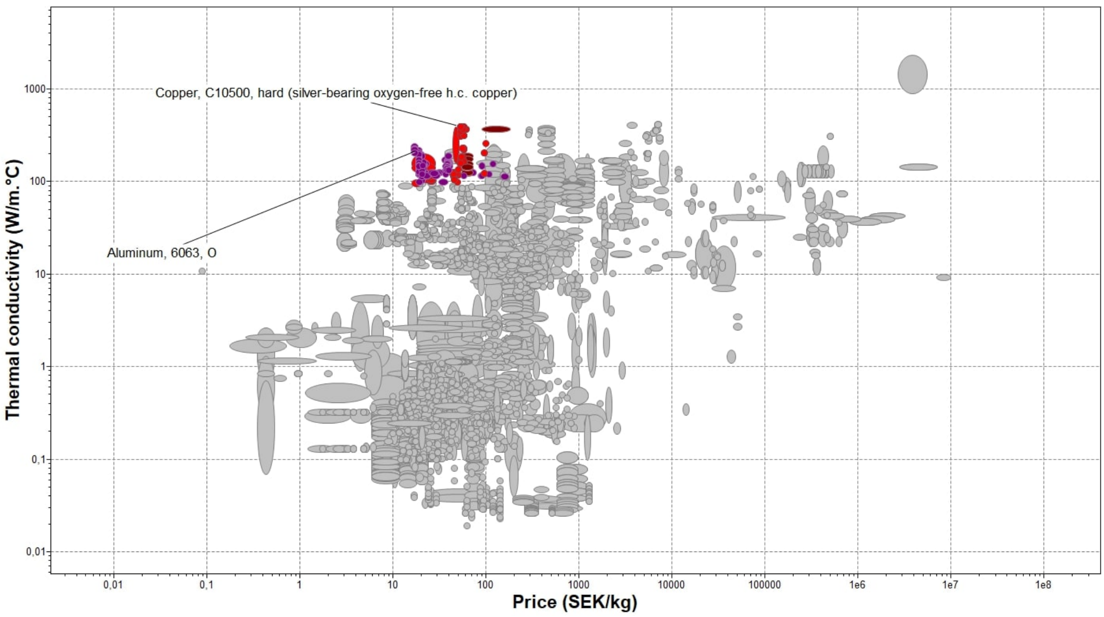

Figure 6: Material selection: Thermal Conductivity vs Price

Upon completing all three eliminations, the remaining material choices were down to one hundred and fifty materials. These materials were grades of different metal alloys and could be grouped into five classes based on their primary material composition: zinc, magnesium, copper, brass, and aluminum alloys. A few grades of these grades were benchmarked against existing busbar material. It was deemed reasonable not to explore all materials grades among these alloys for benchmarking as the material's properties stay mostly the same between different grades of the same alloy. These materials were evaluated against the benchmark material, as demonstrated in Appendix B.

In addition to utilizing the CES Educpack software, comprehensive literature studies uncovered an intriguing material option for the busbar: copper-clad aluminum (CCA) [25]. This innovative composite material combines the desirable properties of copper and aluminum. To evaluate the potential of CCA as a busbar material, it underwent a rigorous benchmarking process against established busbar materials. Compared to traditional options, this comparative analysis assessed CCA's performance, suitability, and distinct advantages or limitations.

The final material choices were narrowed down to copper, aluminum, and Copper-Clad Aluminum (CCA). The material properties of these options are summarized in Table 3. These materials were carefully selected to proceed into the concept development phase, where their feasibility and efficiency were thoroughly examined. Additionally, different combinations of these materials were explored for various components to assess the potential issues arising from material incompatibility and evaluate the overall feasibility of the concepts.

Table 3: Final Material Properties

Material	Material Properties						
	Density (kg/m^3)	Thermal conductivity (W/m K)	Electrical resistivity (ohm-m)	Max Service Temperature (º C)	Young's Modulus (GPa)	Price (SEK/kg)	Tensile Strength (MPa)
Copper (C10500, hard rolled)	8940	397	1.7 x 10-8	200	130	52	210
Aluminum (Al 6063,O)	2720	225	2.8x 10-8	150	80	19	180
Copper Clad Aluminium (CCA)	3630	240	2.6x 10-8	150	70	25	150

4.6.3 Environmental Impact

The emergence of BEVs in recent years is seen as an apt solution to tackle climate impact from the perspective of the automotive sector. Hence, environmental sustainability is one of the key driving factors in material selection for automotive components. This section compares CO_2 emission between the three materials: copper, aluminium, and CCA, in two stages, the primary production stage and the post-use or recyclable stage. These stages play a vital role in material selection and assist in determining the environmental and economic aspects of the material [29].

Primary Production Stage

The primary production stage, also known as the pre-manufacturing stage, marks the beginning of the material life cycle, starting from material extraction from the earth through mining. The raw material is excavated and processed into a useful final product from the earth's crust through several manufacturing and machining processes. Primary production of aluminium is achieved by mining bauxite and uses high energy-intensive processes such as electrolysis to produce aluminium which is then converted into alloys. Hence the pre-manufacturing stage of aluminum is more costly and has higher CO_2 emissions than copper [30] [31].

For pre-manufacturing, the CO_2 emission for aluminium is 13 kg equivalent per kg of material, whereas, for copper, it varies depending upon the percentage of carbon reinforced with copper. Typically carbon is added to copper to add rigidity and strength to the material. The CO_2 emission for copper hence varies from 1.2 kg to 8.5 kg per kg equivalent material; the higher the carbon percentage in copper, the higher the emission [32]. Most automotive parts use copper with two percent carbon and have CO_2 emission of 6.5 kg per kg of material. Since CCA is made using aluminum as base material, the CO_2 emission of CCA during the pre-production stage is comparable to that of aluminum or, in some cases, more due to the requirements of additional energy needed to bond the cooper layer onto the forged aluminum.

Post Use

This is the second stage after converting raw material into a useful product through the primary production stage. This stage accounts for CO_2 emission when the materials are recycled after its use. The recycled materials can aid in replacing the initial raw material with some loss in material properties such as tensile strength and Young's modulus. For post-use, the CO_2 emission of aluminium is 0.5 kg per kg material, and for copper, its 1.5kg per kg equivalent material [30]. A similar argument for CCA mentioned in the primary production stage also applies in the post-use stage. However, there is a drastic difference between CCA and aluminium emissions in this stage since the energy required to break the copper layer in CCA is significantly higher, reducing its scrap value.

The discrepancy in the recycling process can be attributed to copper's higher post-use emissions than aluminum. Copper recycling involves multiple stages, including sorting, shredding, and smelting, which results in higher energy demands. On the other hand, aluminum recycling typically involves a single recycling stage of melting, leading to lower energy requirements. The environmental impact of the final chosen materials is summarized in Table 4.

Table 4: Environmental Impact of Final Materials

	Material		
C02 emissions	**Copper**	**Aluminium**	**CCA**
Pre- manufacturing (kg CO2 -eq/ kg)	**6.5**	**11.5**	**8.5**
Post- Use (kg CO2 -eq/ kg)	**1.5**	**0.5**	**2.5**

5

Concept Development

This chapter entails different methodology tools employed to generate and evaluate concepts for cooling busbar. The chapter discusses simulation-driven designs and concludes with the selected concept's transformation to the final concept for detailed study.

5.1 Idea Generation

Before diving into concept generation, solutions to each sub-functions identified using functional analysis methods were sought. In doing so, it encourages creativity and prevents solutions from being constrained by the project's initial constraints. Several techniques were employed to come up with a large number of ideas for this goal, such as brainstorming and the TRIZ method. The techniques promoted cooperative behavior and increased receptivity to different viewpoints and innovative thinking.

5.1.1 Brainstorming

The brainstorming activity was conducted with the thesis team along with ten members from the traction voltage team at Volvo Trucks. The session introduced the need for this thesis as a problem statement with the alternatives options found through patent search, interviews, and literature study presented to tackle the issue faced in the current scenario. While brainstorming focuses on feasible design ideas as outcomes, its ulterior motive of identifying and comprehending different approaches to problem-solving played a crucial role in this thesis work. Brainstorming was the most beneficial method among all idea generation methods as it encouraged free and spontaneous thinking.

The TRIZ method was also incorporated into the brainstorming session. The audience was presented with ways to solve the problem from diverse industry sectors that correlate to the thesis's weight reduction goals, improved heat dissipation, increased safety, and sustainability. A few inspirational ideas were drawn from existing solutions in other industries related to the thesis work. However, several ideas were deemed challenging concerning their feasibility in the thesis work. Nevertheless, the problem-solving approach to these objectives was insightful in providing several meaningful ideas that would later be incorporated to form concepts in the morphological matrix.

5.1.2 TRIZ Method

TRIZ method, also known as the theory of inventive problem-solving, is a creative thinking method that aims to solve the existing present problem by using primary data and logic from past solutions of either the same or other industry sectors [22] [27]. This thesis explored the TRIZ method to solve the fundamental problem by expanding beyond the confines of the TVPDC box and competitor data to find solutions within or outside the automotive sector. As mentioned earlier, the TRIZ method was incorporated into the brainstorming session to facilitate the audience to draw upon an idea to solve the problem with existing solutions from other sectors. For instance, the concept of cooling busbars using heat pipes, as in the case of computers, was discussed. Similarly, hollow conductors emerged from battery cooling systems in cars.

Apart from design solutions, the TRIZ method also investigated material choices, with CCA being an example primarily used as conductors in home speakers. The alternative materials to TIM, such as foam, phase change material, thermal gel, and pad, were inspired by their applications in the construction and computer sectors [17]. All the inspirational ideas drawn from the TRIZ method aided in providing new dynamic concepts that increase the cooling efficiency of the busbar by faster heat dissipation. However, not all ideas and design concepts were feasible due to space, cost, and manufacturing constraints within the TVPDC box, so they were not considered for further development. Appendix C lists the concepts that emerged during the TRIZ method but were not explored in detail.

5.2 Concept Generation and Evaluation

With the diverse range of ideas generated in the idea generation stage, the next step was to envision working concepts by combining the ideas generated from each sub-function. This section explores various concept generation methods while providing valid evaluation criteria to eliminate and select said concepts. The reasoning and justification for each decision made are mentioned in the subsequent sections.

5.2.1 Morphological Matrix for Base Concept Generation

The morphological matrix was implemented to observe the interactions between the diverse sub-solutions generated in the idea generation phase when merged into a concept. The morphological matrix in Appendix D contains brief sketches of each sub-solution for each sub-function. The sketches enabled better comprehension of the product functionality, a cooling system for the busbar. The morphological matrix also aided in understanding the compatibility of different sub-solutions when merged into a concept, thereby forming the base criteria for assessing the feasibility of the concept.

The traditional approach for morphological matrix employs a permutation and combination of each sub-solution for each sub-function, resulting in more than 100,00 outcomes [22]. Due to the time constraints and to enable an efficient methodology, a few sub-solutions that were deemed outside the project scope were eliminated. This still resulted in a handful of sub-solutions and numerous possible combinations. Hence the decision was made to split the 13 sub-function into two categories and then combine them to form an entire concept.

Critical sub-functions: These sub-functions contribute to the cooling of busbars. The fulfillment of the requirements list in the priority order is achieved through the sub-solutions to these sub-functions. The identified critical sub-functions are:

1. Specify Main Busbar
2. Specify Branch Busbar
3. Heat Dissipating Structures
4. Optimize Cross-section
5. Place Cooling Channel
6. Configure cooling Channel
7. Cooling Method
8. Heat Dissipating Material

Supporting sub-functions: The remainder of the sub-functions that were not included in the critical sub-functions are known as supporting sub-functions. When combined with these functions, the sub-solutions in the critical sub-functions work as complements and improve the overall functionality of the proposed solution.

The sub-functions were divided into two groups, making it possible to create concepts from two different morphological matrices representing various solutions grouped in the matrix. This was seen as advantageous because it allowed for the management of the sizable solution space. The first morphological matrix comprised of only sub-solutions to the critical sub-functions, generating twenty diverse concepts as shown in Table 5 and 6.

Table 5: Morphological Matrix Base Concepts 1-10

Sub-function	Concept Solutions									
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
F1: Specify main busbar	Solid busbars	Solid busbars	Solid busbars	Hollow	Hollow	Hollow	Laminar	Hollow	Hollow	C- shape busbars
F2: Specify branch busbar	Laminar	Solid	Laminar	Solid	Laminar	Solid	Laminar	Laminar	hollow	solid
F3: Heat- dissipating structures	Fins	coolant and Fins	Hollow tube	Fins	coolant	Hollow tube	Heat exchanger and sink	Coolant	Coolant and holes	Coolant and fins
F5: Optimize cross-section	Square	Square with rounded corners	Rectangle	Square	Inner and hollow cross-section are rectangle rectangle	Rectangle on inner and outer area of hollow square	Rectangle	Outer area rectangle and inner hollow square	Inner and hollow cross-section are rectangle	Busbar has C cross-section and coolant rectangular
F8:Place cooling channel	Outside the housing	Underneath the housing	Outside the housing	Underneath the housing	Underneath the housing	Underneath the housing	Underneath the housing	Through the busbars	Through the busbars	Inside the housing
F9: Configure cooling channels	none	One	one	none	one	More than two	More than two	Two	Two	Two
F12: Cooling method	Natural convection using air	Indirect Cooling using Liquid	Indirect Cooling using Liquid	Natural convection using air	Indirect cooling using liquid	Indirect cooling using liquid	Indirect cooling using liquid	Direct cooling using liquid	Direct cooling using liquid	Indirect cooling using liquid
F13: Heat Dissipating material	Copper (Cu)	Copper (Cu)	Copper (Cu)	Aluminium (Al)	Copper (Cu)	Copper (Cu)	Copper (Cu)	Copper (Cu)	Copper Clad Aluminium (CCA)	Copper (Cu)

Table 6: Morphological Matrix Base Concepts 10-20

Sub-function	Concept Solutions									
	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20
F1: Specify main busbar	C- shape busbars	C- shape busbars	Solid busbars	Solid busbars	Solid busbars	Hollow	Hollow	Solid	Hollow	Solid
F2: Specify branch busbar	Laminar	Solid	Laminar	Solid	Solid	Hollow	Solid	Hollow	Solid	Hollow
F3: Heat- dissipating structures	Coolant	Coolant and holes	Coolant	coolant	Heat exchanger and sink	Holes and fins	Holes and fins	Holes and fins	Coolant and fins	Coolant
F5: Optimize cross-section	Busbar has C cross-section and coolant rectangular	Busbar has C cross-section and coolant	Rectangle	Circular	Circular	Rectangle with rounded corners	Outer area rectangle and inner hollow	Rectangle with rounded corners	Outer area rectangle and inner hollow	Recantagle and square hollow busbar
F8:Place cooling channel	through the busbars	Underneath the housing	Underneath the housing	Inside and Underneath the housing	Inside the housing	inside the housing	Outside the housi	Underneath the housing	inside the housing	Inside and Underneath the housing
F9: Configure cooling channels	Two	one	One	Two	Two	One	None	Two	More than Two	Two
F12: Cooling method	Direct liquid cooling and natural air convection	Indirect cooling using liquid	Indirect cooling using liquid	Indirect cooling using liquid	Indirect cooling using liquid	Liquid and air cooli	Natural convection using air	Direct liquid cooling and natural air	Indirect cooling using liquid	Indirect cooling using liquid
F13: Heat Dissipating material	Copper (Cu)	Copper Clad Aluminium (CCA)	Copper (Cu)	Copper (Cu)	Aluminium (Al)	Copper (Cu)	Aluminium(Al)	Cu main busbar and Al branch busbar	Copper Clad Aluminium (CCA)	Al main busbar and Cu branch busbar
			Existing							

The concepts were predominantly based on the *cooling method* sub-function. As a result, the concepts were classified into two different trains of thought, namely, air cooling and liquid cooling, to cool down the busbar effectively. The additional sub-functions and their associated sub-solutions were combined to see which concept best complemented these two lines of reasoning. For instance, the air cooling design method could be coupled with fins on busbars and a heat sink to increase the heat transfer rate between the contacting surfaces. Similarly, a hollow busbar or having more than one cooling channel can increase the cooling rate for a liquid-cooled design.

The air and liquid-cooled concepts combined these ideas with other sub-functions solutions, such as optimizing cross-sections where different geometry profiles for busbar were explored. The concepts were later combined with heat-dissipating material, constituting the different material choices for the busbar. Consequently, an entire concept was created by methodically tracing the concepts from one sub-function to another and evaluating how well the ideas were integrated.

5.2.2 Elimination Matrix for Base Concept Generation

With twenty diverse concepts in the handcrafted morphological matrix, it became imperative to determine whether they aligned with the project scope. Hence, the elimination matrix was deemed an appropriate method to assess them using predefined metrics, as mentioned in section 3.6. Cooling efficiency and safety, as stated in the requirement list by the thesis and Volvo Trucks teams, were of utmost importance.

From the literature study, it became evident that liquid cooling is superior to the air cooling method. Therefore, any concepts that utilized air cooling and failed to meet all requirements were eliminated. Similarly, concepts with safety concerns were also eliminated. Finally, the concepts were evaluated based on their feasibility. Any concepts that necessitated redesigning the existing junction box were eliminated, thereby adding to the cost. Consequently, these elimination criteria reduced the number of concepts from the morphological matrix down to ten, as seen in Table 7.

Likewise, the elimination matrix was applied to the supporting sub-functions morphological matrix. The main elimination criteria here were the compatibility of sub-solutions with the existing design, cost, and feasibility within the scope of the thesis. As a result, the initial eighteen concepts from the supporting sub-function morphological matrix were reduced to seven.

Table 7: Elimination Matrix of base concepts

Elimination Matrix									
Solution Alternative	Solves main problem more effectively	Fulfills all demands	Compatible	Reasonable cost	Safe	Fits portfolio	Comment	Decision	
1	-	-	+	+	+	+	natural air cooling not effective than exsiting cooling desing	-	**Criteria fulfillment**
2	+	+	+	-	+	+	costly and require more solid busbars	-	+ Yes
3	+	+	-	?	?	+	Research cost and safety method for improvement	+	- No
4	-	+	+	-	+	-	costly, needs fans for efective cooling	-	? More information needed
5	+	+	+	?	+	+	Research cost	+	! Check with specification
6	+	+	+	+	+	+		+	
7	+	-	-	-	+	-	costly, needs redesign of exsiting solution	-	
8	+	+	+	?	+	+	more effective cooling, need to research cost	+	**Decision making**
9	+	+	?	+	?	+	check feasibility of cooling inside the housing and safet aspec	+	+ Continue
10	+	-	+	+	?	+	research more on improving safety	+	- Remove
11	+	+	+	?	+	+	research cost of insulating the coolant tube	+	? More information needed
12	+	-	+	+	+	!	CCA has less current capacity than copper and fails melting point requirement	-	! Check with specification
13	-	+	+	+	+	+	existing design, taken as reference for comparing concept	+	
14	+	-	-	-	+	+	circular cross-section requires larger dimension for achieving required current capacity	-	
15	+	-	-	-	+	+	costly, needs redesign of exsiting solution	-	
16	+	+	-	-	+	-	costly and requires design of supporting systems	-	
17	-	+	+	+	+	+	less efffecive cooling than existing solution	-	
18	+	+	+	+	+	+		+	
19	+	-	?	+	-	+	less safe to use cooling inside without hollow tube and CCA not ideal material	-	
20	+	+	?	?	+	+	research cost and possibiltiy of using the concept in the existing location	+	

However, instead of discarding certain aspects of the base concepts derived from the morphological matrices entirely, the focus shifted towards selecting specific sub-solutions that showed promise for developing improved concepts. These selected sub-solutions became valuable sources of motivation for integrating various sub-functions into a cohesive overall design.

To further investigate the ten prevailing concepts, additional research was conducted. This research aimed to understand how the multitude of sub-solutions identified in the morphological matrix could synergistically work together. A deeper insight into the potential integration and functionality of the concepts was gained by carefully examining the interplay and compatibility of these sub-solutions.

5.2.3 Morphological Matrix for Full Concept Generation

As mentioned, the decision was made to split the sub-functions into two categories to limit the number of possible combinations in the morphological matrix. This methodology resulted in the two morphological matrices during product development. At this level, refined base concepts from the first morphological matrix were combined with sub-solutions solving the supporting sub-functions. In order to enhance the base concepts and maintain diversity among the new sub-solutions, additional sub-solutions were picked. The concepts generated by this second morphological matrix are complete concepts, addressing all sub-functions.

5.2.4 Pugh Matrix for Full Concept Generation

All the remaining concepts from the elimination matrix and the second morphological matrix are aligned with the thesis scope and objectives. However, comparing these concepts and selecting the most promising ones became necessary. A Pugh matrix was utilized to achieve this, with criteria selected from the requirement list. Multiple iterations of the matrix were carried out until the results converged.

The existing busbar cooling system was used as a reference in the first iteration, and all other complete concepts were compared against it. As a result, two out of the remaining ten concepts received a lower rating than the existing design. Interestingly, these two concepts employed indirect liquid cooling, similar to the existing design, and therefore had lower heat dissipation. From this matrix iteration, it was inferred that indirect liquid cooling is not the most optimal cooling method, and changing the cooling channel placement affects the compactness of the design. However, the entire concept was not dismissed; promising elements, such as specific sub-solutions, were identified for inspiration and incorporation into future concepts. Two more matrix iterations were conducted, and the final iteration is presented in Table 8.

Table 8: Pugh Final Iteration for Base Concepts

Criteria	Alternatives									
	C1	C2	C3	C4 (ref)	C5	C6	C7	C8 (existing)	C9	C10
Provide more effective cooling	-	-	-	0	+	-	+	-	+	-
Should have same or improved electrical insulation for safety	0	0	0	0	0	+	+	0	+	+
Should weigh low	-	0	-	0	+	-	-	-	0	0
Should be easy to manufacture	+	0	+	0	-	+	+	+	0	0
Design should be compact	-	+	-	0	+	0	+	-	+	-
Should dissipate heat faster	-	-	-	0	+	-	0	-	-	+
Should be easy to assemble parts	0	-	-	0	-	+	+	+	-	-
Use same exchangeable parts as currently used	+	-	-	0	-	-	-	+	-	-
Should have same or improved current carrying capacity	+	0	+	0	-	+	+	+	-	-
Should not require new supporting modules	-	0	+	0	-	+	-	+	-	-
Design should be stiff and have bending less than 1 mm in Z direction	+	0	+	0	-	+	+	+	+	0
Total positive	4	1	4		4	6	7	6	4	2
Total negative	5	4	6		6	4	3	4	5	6
Total neutral	2	6	1		1	1	1	1	2	3
Sum	-1	-3	-2		-2	2	4	2	-1	-4
Ranking	3	5	4		4	2	1	2	3	6
Further Development	inspiration	no	no		no	yes	yes	yes	yes	no

While the first iteration provided inference, as stated above, it also suggested the best concept among all ten concepts. The best concept C7 employed a direct cooling method, and this served as a reference for the next iteration. Hence, it inferred that air-cooled concepts were less feasible due to their requirement of new supporting modules to the existing design. The remaining concepts were revised and cross-pollinated to generate more promising concepts. The final iteration of the Pugh matrix was conducted using cross-validated results obtained from the first two iterations. This iteration confirmed that using the direct liquid cooling method improved both the design's heat dissipation rate and compactness.

5.2.5 Kesselring Matrix for Concept Evaluation

The Pugh matrix resulted in five concepts that need further evaluation to select the best concept for further development. The concept evaluation was achieved using the Kesselring matrix, with each requirement in the requirement specification allocated a specific weight as shown in Appendix F. The method and process for implementing the Kesselring matrix are already discussed in section 3.6.3. The values are translated into decimals corresponding to their percentage value.

The five concepts were inputted into the matrix with subsequent evaluation of each requirement. The main function and the associated sub-functions were discussed and compared against each requirement corresponding to their percentage value. During the evaluation of the Kesselring matrix, specific estimations and assumptions had to be made. For example, the weight of the concept design was hard to determine without a CAD model; as such, the solutions attributing to the concept's weight were backed by engineering knowledge, reason, and estimation from the thesis team. Similarly, gauging cooling and heat dissipating efficiency was only possible with comprehensive and conclusive analysis results. Hence the weight allocation to these criteria was based on a literature study and reasoning from the thesis team.

Table 9: Kesselring Matrix for Full Concepts

Evaluation Criteria	**Concepts**												
	Ideal			**C1**		C6		C7		C8		C9	
Criteria	**w**	**a**	**t**	**a**	**t**	**a**	**t**	**a**	**t**	**a**	**t**	**a**	**t**
Cooling method efficiency	0.2	5	1	2	0.4	3	0.6	4	0.8	3	0.6	4	0.8
Electrical insulation safety	0.4	5	2	4	1.6	4	1.6	4	1.6	4	1.6	4	1.6
Design should weigh low	0.1	5	0.5	3	0.3	4	0.4	4	0.4	2	0.2	5	0.5
Heat dissipation efficiency	0.15	5	0.75	2	0.3	4	0.6	5	0.75	3	0.45	4	0.6
Design should be compact	0.01	5	0.05	2	0.02	3	0.03	4	0.04	4	0.04	3	0.03
Requirement of new supporting modules	0.01	5	0.05	4	0.04	5	0.05	3	0.03	5	0.05	3	0.03
Current carrying capacity	0.04	5	0.2	3	0.12	3	0.12	3	0.12	3	0.12	3	0.12
Should be easy to manufacture	0.05	5	0.25	5	0.25	3	0.15	3	0.15	5	0.25	2	0.1
Should be easy to assemble	0.02	5	0.1	4	0.08	4	0.08	4	0.08	4	0.08	3	0.06
Use same exchangable parts as currently used	0.01	5	0.05	5	0.05	1	0.01	2	0.02	5	0.05	2	0.02
Stiffness less than 1mm in Z direction	0.01	5	0.05	5	0.05	4	0.04	5	0.05	5	0.05	3	0.03
Sum	1	55	5	39	3.21	38	3.68	41	4.04	43	3.49	36	3.89
Ranking				5		3		1		4		2	
Decision	Propose Concept 7 and 9												

The Kesselring matrix resulted in two concepts, C7 and C9, for further exploration and development, as shown in Table 9. Based on their unique feature, these concepts are aptly named for easier reference. Hence C9 was named as *Hollow Busbar Design* as it incorporated a hollow busbar through which water is directly passed for cooling. Similarly, C7 was renamed as *C- shape busbar* due to its unique feature of using a busbar in the shape of C and a coolant tube attached underneath it.

5.3 Simulation Driven Designs

The two concepts that emerged at the end of the Kesselring matrix, namely the *Hollow Busbar Design* and *C-shape Busbar*, were further developed into CAD designs to visualize the concepts. Simulations were performed on these designs to test their functionality. Simulation-driven designs allowed for the assessment of performance using the same design parameters as the existing design.

The concept designs underwent progressive iterations based on insights gained from simulation results. For the *Hollow Busbar Design*, variations in the hollow channel's cross-section were explored to understand its impact on cooling efficiency. As for the *C-shape busbar*, different material combinations between the busbar and the coolant channel were investigated to determine the effect of material compatibility on achieving optimal temperature reduction for the busbar.

In addition to the simulation findings, the simulation-driven design approach addressed specific challenges. For the *C-shape busbar*, it resolved the issue of mounting two components and effectively cooled busbars connected to distant connection ports, such as OCEPS and ePTO, which were significantly further away from the cooling surface. These distant busbar ports were identified as the hottest points, reaching maximum temperatures, as depicted in Figure 7.

Based on the insights obtained from these simulations, a design revision was conducted to address these challenges. The subsequent section will discuss the revised changes that transformed the selected concept into the final concept.

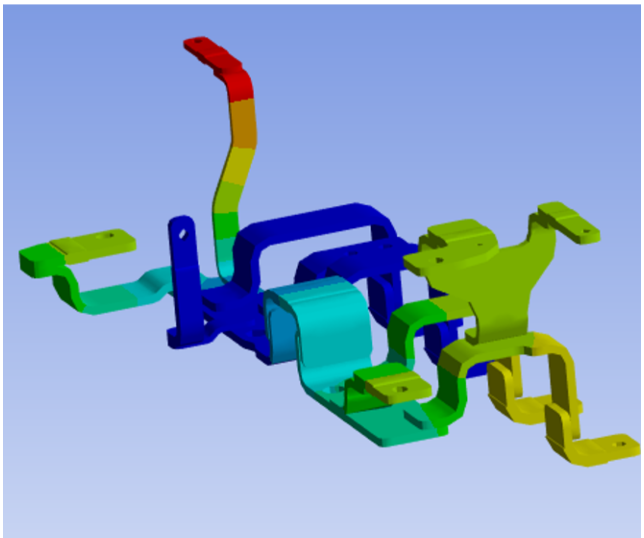

Figure 7: Simulation Driven Design Result

5.4 Transformation to Final Concept

The simulation-driven design process yielded conclusive evidence regarding areas of improvement in the two concepts. The transformation process incorporated these suggestions into the proposed design concepts. For the *C-shape Busbar Design*, a key issue identified was mounting between the busbar and the coolant tube underneath it. Several design solutions, such as clamps, welding, bolts, slot mechanisms, or combinations thereof, were considered to address this problem. However, assessing the feasibility of these ideas concerning the existing concept solution was crucial. This evaluation involved revisiting the Kesselring matrix using engineering knowledge and the requirement specification. After careful consideration, the best solution was a combination of welding and bolts, as depicted in Figure 8.

In the case of the *Hollow Busbar Design*, the geometry parameters were optimized using the design of experiments (DoE) methodology. This approach helped select a geometry profile that improved cooling efficiency or heat dissipation rate. The initial design concepts, the C shape and Hollow busbar addressed the challenge of cooling busbar ports located further away from the cooling surface. As a result, the design was transformed by modifying the initial flat coolant channel into a U-shaped path with an elevated surface path, as depicted in Figure 9. This modification effectively addressed the busbar ports located at the heat source.

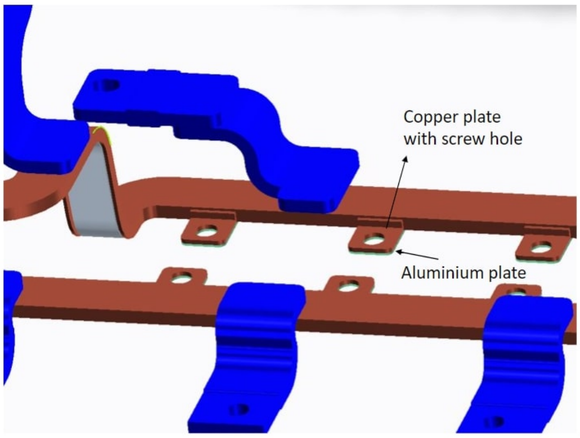

Figure 8: Mounting of C Shape Busbar

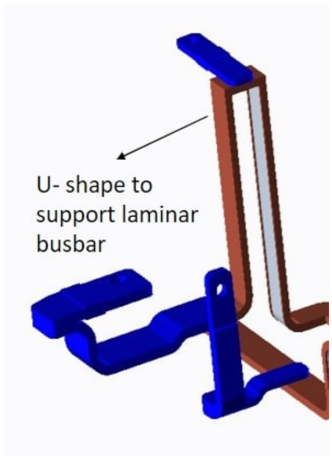

Figure 9: U shape to Cool Laminar Port

Considering that the purpose of the thesis was to develop a safe and efficient concept for cooling busbars, it is essential to address the safety aspects in the CAD models of the concepts. The next logical step would be to identify and resolve any potential safety issues that are evident in the two concepts. Several design iterations addressed safety concerns, incorporating additional ideas into the initial concept designs.

6
Final Concept

This chapter discusses the final concepts obtained from the transformation of concepts in Chapter 5. Simulations and the comparison of their results compared with the existing busbar cooling system are also discussed in this chapter. The chapter is concluded with a revisit to the fulfillment of the requirement specification.

6.1 Concept overview

This project investigates the concept development process of cooling systems for high-current busbars in truck electrical distribution boxes. It focuses on utilizing a scientific approach to product development, concept screening, and selection. Two potential designs, namely the hollow busbar and the C-shape busbar, have been identified through a series of disciplined scientific processes. These designs possess both strengths and weaknesses while meeting various requirements and demands related to performance, manufacturing, and installation methods. A preliminary examination of similar products offered by other companies has been conducted further to validate the feasibility of these two busbar designs. This examination confirms the designs' viability and alignment with industry standards. There exists a scarcity of mature, market-ready extreme high-current busbar products integrated with cooling systems. Therefore, this project represents an innovative exploration within truck electrical distribution boxes.

Table 10 lists the significant sub-solutions to the identified sub-functions for both design concepts: the hollow busbar design and the C-shape busbar design. The common feature of these concepts is that their cooling method is direct liquid cooling.

Table 10: Sub-solutions for Proposed Concepts

Sub-function		C- Shape Busbar Design	Hollow Busbar Design
Critical sub functions	F1: Specify main busbar	C- shape busbars	Hollow
	F2: Specify branch busbar	Laminar	Laminar
	F3: Heat- dissipating structures	Coolant	Coolant
	F5: Optimize cross-section	Busbar has C cross-section and coolant rectangular	Rectangle hollow structure
	F8:Place cooling channel	through the busbars	through the busbars
	F9: Configure cooling channels	Two	Two
	F12: Cooling method	Direct liquid cooling and natural air convection	Direct liquid cooling and natural air convection
	F13: Heat Dissipating material	Copper (Cu) and Aluminium	Copper (Cu)
Supporting sub functions	F4: Mount components	Welding and Bolts	Welding and Bolts
	F6: Enable servicing	Different Components	Same components
	F7: Provide thermal Insulation	Thermal Insulating material (TIM)	Thermal Insulating material (TIM)
	F10: Ensure coolant recylcability	Cooling channel outlet to resorvoir and to cooling container	Cooling channel conncetion from intlet to outlet
	F11: Provide electrical Insulation	Insulation material on outside of coolant path	Insulation material on inside of coolant path

6.2 Existing Design

In the current design, the junction box is completely enclosed, and only an external cooling plate is attached to the bottom surface. This plate enables the flow of coolant liquid, indirectly cooling the walls of the junction box. However, thermal-electric simulations have revealed that the hottest portion of the entire busbar system is located in the laminar busbar, which connects the connection ports, and the main busbar, which connects two laminar busbars. The issue stems from the suspended design of the laminar busbar, which prevents direct contact with the bottom wall. Consequently, there is a lack of an efficient means to dissipate heat using the coolant. The cooling options for the laminar busbar are limited to two methods: a small amount of cooling through air convection and conduction to the solid main busbar at the bottom. The heat is then transferred and dissipated to the closely connected TIM and the bottom wall of the junction box. However, these heat transfer pathways have low heat transfer rates and are incapable of handling the normal operating pressures of the next generation of high currents exceeding 700A and voltages of 1000V.

6.3 Hollow busbar

Hollow busbars have emerged as an efficient cooling solution in various applications, offering advantages in high-power transmission systems and electric motors. The internal hollow structure of the busbars facilitates effective air cooling, ensuring rapid heat dissipation and maintaining the temperature within acceptable limits. Integrating hollow conductors within electric motor stators also enables direct liquid cooling, enhancing cooling efficiency and overall motor performance. By embracing hollow busbars, the field of busbar cooling continues to drive innovation and contribute to advancements in power transmission and motor technology [14].

The hollow structure of busbars enables improved heat conduction within the system, effectively removing excess heat from the laminar busbar. Selecting materials with high thermal conductivity further enhances heat transfer performance. For this project, a copper busbar is selected, and the insulation material is epoxy resin between the conducting copper and the coolant following through it. The hollow busbar design's enhanced cooling efficiency and heat conduction capabilities make it well-suited for handling high currents exceeding 700A without compromising safety.

6.3.1 Motivation for Hollow Busbar Design

The overheating issue of the suspended laminar busbar within the junction box necessitates the adoption of a hollow busbar design. This design transforms the entire busbar into an integrated system with a strategically planned coolant path, allowing the coolant to reach every port and the laminar busbar itself effectively. The suspended busbar design offers several advantages, including direct contact between the coolant and the busbar, ensuring efficient cooling. It also enables rapid coolant flow throughout the solid busbar, facilitating effective heat dissipation. Additionally, the design allows for heat conduction from the high-temperature points of the laminar busbar to the solid busbar, preventing heat over-accumulation. As a result, the maximum temperature of the entire busbar system is significantly reduced.

6.3.2 Design Specifications of Hollow Busbar

Once the identification of solid busbars that need to be replaced with hollow busbars is completed, the next step is establishing the coolant path. Following a similar approach to the current design, the smaller laminar busbars are precisely welded onto the hollow busbar. These compact laminar busbars are positioned in close proximity to the coolant, ensuring that their operating temperatures remain low. This proximity allows for efficient heat dissipation at the source of heat generation. Importantly, replacing or integrating these smaller laminar busbars into the hollow coolant path is not required, thereby simplifying the overall design. In Figure 10, the compact laminar busbars are represented as blue components, connecting the main busbar with the current carrying connection ports.

In the hollow busbar design, plates are welded onto the hollow tube. These welded plates feature embossed circular holes, facilitating the mounting of the hollow busbar onto the junction box using screws. To ensure electrical insulation and prevent contact with the current-carrying busbars, these screws are enclosed within a protective plastic housing. Additionally, during the manufacturing process, an electrical insulation coating is applied to safeguard the inner cross-section of the hollow busbar. Typically, this coating consists of epoxy resin, effectively protecting the inner surface of the busbar and preventing any electrical contact or short-circuiting.

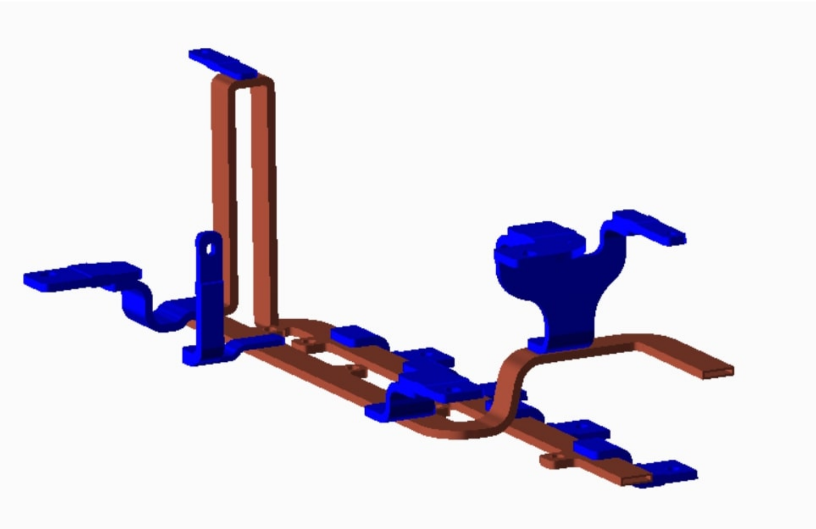

Figure 10: Hollow Busbar Design

6.3.3 Challenges of Hollow Busbars

Hollow busbars have distinct characteristics compared to their counterpart, hollow conductors. They are specifically designed for the efficient cooling of busbars and place greater emphasis on safety considerations. However, several significant challenges must be addressed before implementing the hollow busbar design. These challenges were thoroughly discussed during an interview with Luvata [33]:

- **Minimum Corner Radius of Hollow Tube:** The corner or bending radius of the hollow busbar tube significantly impacts cooling efficiency. Smaller radii cause flow resistance and pressure drop, reducing efficiency, while sharp corners create turbulence and inefficient heat transfer. Luvata's interview determined that the minimum corner radius should be three times the busbar weight. However, modifying the coolant pathway is restricted by surrounding module design specifications. Hence balancing corner radius, design constraints, and cooling performance is crucial for an effective hollow busbar design.

- **Manufacturing Process and Pricing:** The interview with Luvata yielded valuable insights into the manufacturing process and cost considerations of producing hollow busbars. Metal extrusion is the primary method employed for manufacturing hollow busbars. This process offers cost-effective production. However, as the busbar's length, width, and thickness increase, the manufacturing cost also tends to increase. Therefore, the hollow busbar's size and dimensions can impact the production cost.

- **Electric Insulation for Coolant Tube:** During the interview with Luvata, the possibility of coating the hollow cross-section of the busbar design was discussed. It was determined that electrical insulation of hollow busbars is achievable through electroplating. However, the complexity and cost of the process depend on the design's intricacy and the type of insulation material used. Coating the hollow busbar's cross-section requires specialized techniques and materials, which can contribute to increased complexity and higher costs.

The challenges encountered during the design of the hollow busbar concept presented a significant obstacle when considering its viability as the final concept. One of the main concerns revolved around the cost associated with providing electrical insulation for the hollow busbar. This factor heavily influenced the decision-making process, as the thesis emphasized cost considerations. Nonetheless, simulations were conducted to compare the performance of this design with the preferred alternative, the C-shaped busbar.

6.4 C-shape busbar

Considering the insights gained from Luvata and after extensive product development, the C-shape busbar design emerged as the best alternative among the two final concepts. As the name implies, the design employs a C-channeled busbar made of copper. Cooling of this busbar is achieved through a rectangular hollow aluminium tube that passes liquid directly through it. These two components are joined together to form a complete busbar cooling system.

6.4.1 Motivation for C shape Busbar Design

With the cooling tube coated on the outside, the C-shape busbar can snugly fit around the tube. This design increases the contact area between the busbar and the tube, enhancing the efficient transfer of heat by the coolant. However, it also provides added structural stability, making it capable of withstanding high-frequency vibration tests. Moreover, the shared pathway for the tube and the busbar allows them to be perfectly attached, significantly improving assembly efficiency.

6.4.2 Design Specifications of C-shape Busbar

The proposed new design of the busbar shape effectively addresses the challenges associated with the inner wall coating of the hollow busbar. This innovative design divides the busbar into two separate components, each serving a specific function: one for carrying high current and the other for facilitating coolant flow. By adopting this approach, the primary focus was on applying an electric insulation material coating exclusively to the exterior of the cooling tube.

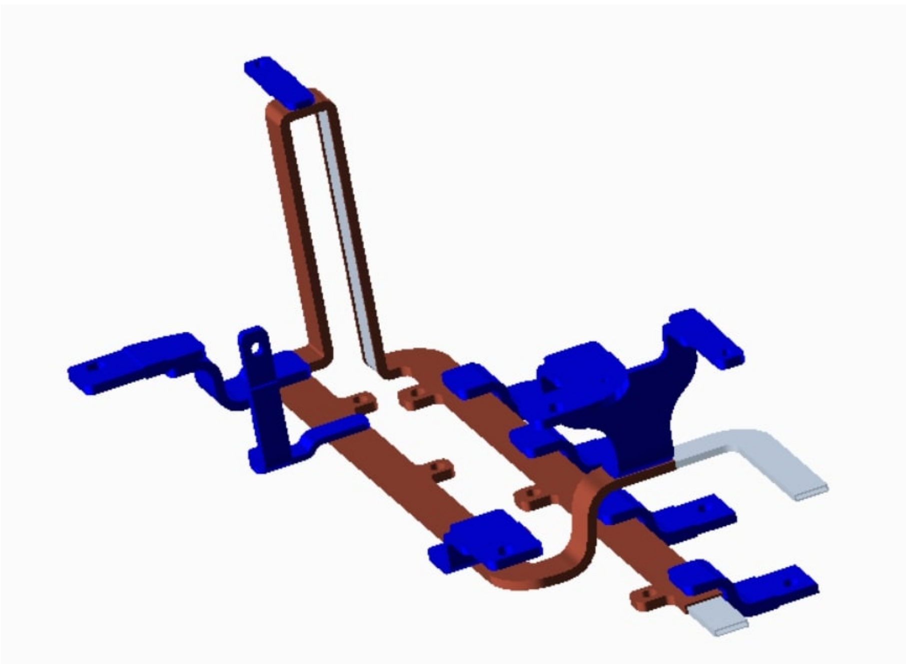

Figure 11: C Shape Busbar Design

The C-shape busbar design follows a similar approach to the hollow busbar by incorporating welded plates onto the copper (brown components in the figure) and aluminium components(the grey component in the figure). These welded plates feature embossed circular holes to accommodate screws for secure assembly. The copper and aluminium components are separate parts, so they can be designed with suitable tolerances to ensure proper fit and alignment. The gap between the components is reinforced with a thermal TIM to enhance heat dissipation.

The choice to prioritize the outside coating of the tube is based on the fact that it leverages a well-established technology readily available in the market. Three commonly employed coating methods, namely liquid potting, shrink-wrap, and powder coating, were thoroughly explored. After careful evaluation, the shrink-wrap method was selected for the C-shaped design due to its ease of installation and cost-effectiveness. The shrink-wrap method uses rapid heating and cooling processes to tightly wrap the insulation material around the desired geometry.

6.5 Simulation Process

Upon completing the modeling phase of the product development, it was crucial to conduct precise thermal- simulations to replicate the natural working environment of the busbar accurately. In collaboration with the Volvo Team, two specific operating scenarios were identified for in-depth analysis.

The first scenario involves the truck being stationary during full-power charging, where the busbar receives a high current input from the charging ports. The current then flows through the main busbar, primarily exiting through the ports connected to the battery. The second scenario considers the truck operating at high speeds with the electric motor running at full power. In this situation, most of the high current is supplied from the battery to the busbar, with a majority flowing toward the EMDs. At the same time, a smaller portion is directed toward fans, OCEPS, and other ports.

Considering the complexity of the electrical equipment employed in the truck during operation, the project focuses on conducting electric-thermal simulations specifically for the second scenario, which represents the operational condition of the truck. The main objective is to evaluate the maximum peak temperature generated during peak current distribution across the busbars.

By simulating the thermal-electric behavior of the busbar in this operational scenario, the project aims to assess the busbar's thermal performance and identify potential hotspots. This information is crucial for ensuring the reliability and safety of the busbar system during high-power operations.

6.6 Steady State Electric-Thermal analysis

The simulation process was initiated after conducting a thorough study of the thermal-electric module in ANSYS and collecting design data for the busbar in the current trucks. This analysis helped in understanding and optimizing the interdependent behavior of heat generation and electrical conduction in the busbar. By optimizing the coolant channel, the cooling system was efficiently designed to dissipate heat and regulate temperature.

6.6.1 DoE Setup

After implementing steady-state thermal-electric analysis in ANSYS, a parametric study was conducted to investigate the relationships between various parameters. A design of experiments (DoE) method was employed to achieve this. The parameters of interest in this study are the geometry parameters, namely the busbar's height, thickness, and width. Additionally, the maximum temperature and weight of the designed geometry were the focal points of the parametric results.

The DoE involved maintaining one parameter constant while observing its impact on the maximum temperature and weight outcomes. In order to obtain diverse results, 40 design points were analyzed parametrically with a fixed height of 5mm, while the thickness and width were varied. This process was repeated for another set of 40 design points, but this time with a height of 6mm. Since the intention was to replicate an existing busbar, the width was constrained to 34mm. However, these constraints can be easily adjusted to facilitate a more comprehensive design study. Correlation plots were subsequently generated using Python to represent the relationships between the parameters visually.

6.6.2 Boundary Conditions and Material Parameters

Specific material parameters for the copper busbar, aluminum cooling tube, and TIM material were derived from CES Edupack and Volvo's intranet search portal. For the existing design, heat diffusion involves convection with air and heat convection with coolant through contact with the TIM material at the bottom.

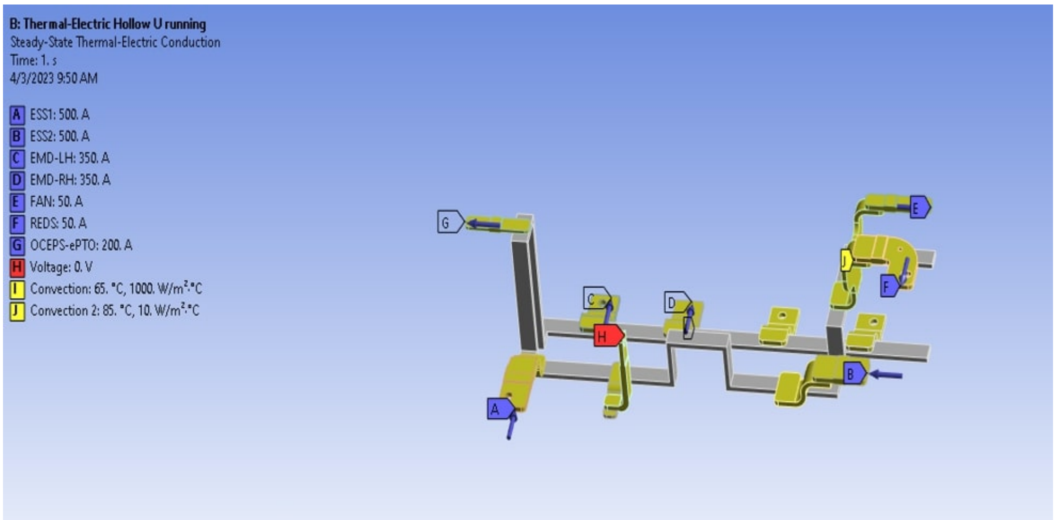

Figure 12: Thermal-Electric Analysis Boundary Conditions

As discussed in the previous section, only the vehicle's operating state was considered for simulation. Hence the magnitudes and directions of the currents at each connection port are illustrated in Figure 12. The analysis was performed considering the three different designs: existing design, hollow design, and C-shape design, to compare the concepts while also cross-validating the results.

For the hollow design, simulating the fluid flow through the tubes would require approximately 200 iterations of CFD calculations to achieve convergence. However, conducting such a high number of CFD calculations would hinder the iterative modifications and adjustments to the model and subsequent thermal-electric simulations. Therefore, a simplified approach was adopted, replacing dynamic fluid analysis with static convection analysis.

6.6.3 Analysis of Results

The findings from the thermal-electric simulations are presented in Figures 14 and 13. In the existing design, the hottest region was the busbar attached to the OCEPS connection port. The design's elongated and laminar busbar structure led to a rapid concentration of heat, making it challenging to conduct the heat towards the bottom main busbar for conduction-based heat dissipation. In contrast, the hollow busbar and C-shape busbar demonstrated effective heat dissipation due to the proximity of the coolant tubes to all the ports, facilitating efficient heat transfer.

Figure 13 presents the maximum temperature of the hollow busbar design under the predefined boundary conditions, with a recorded value of 73°C. Conversely, Figure 14 illustrates a maximum temperature of 73.4°C for the C-shape design. Although both designs exhibit similar maximum temperatures, their geometry profile differs.

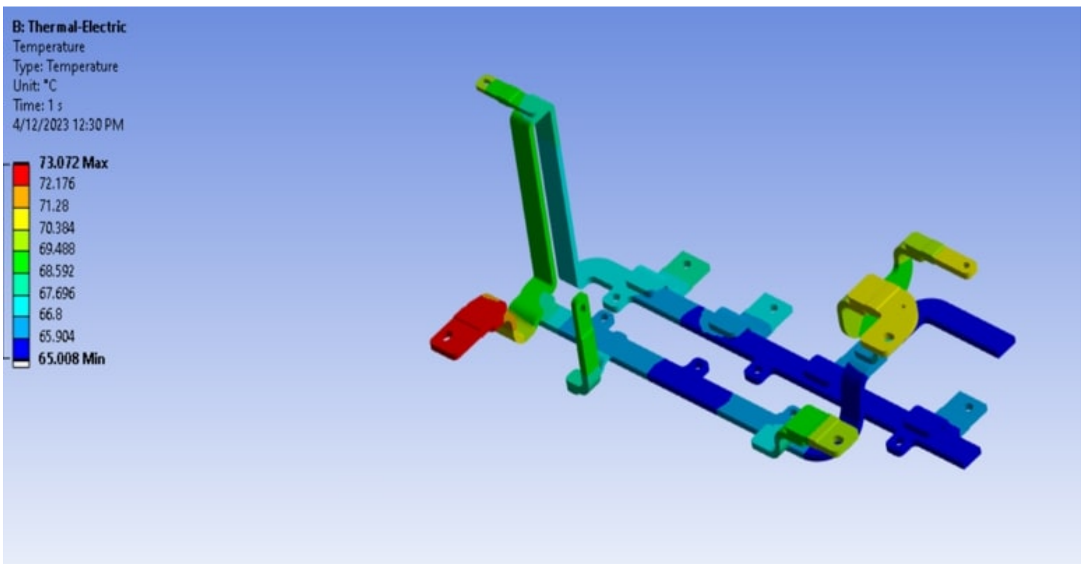

Figure 13: Thermal–Electric analysis of Hollow Busbar Design

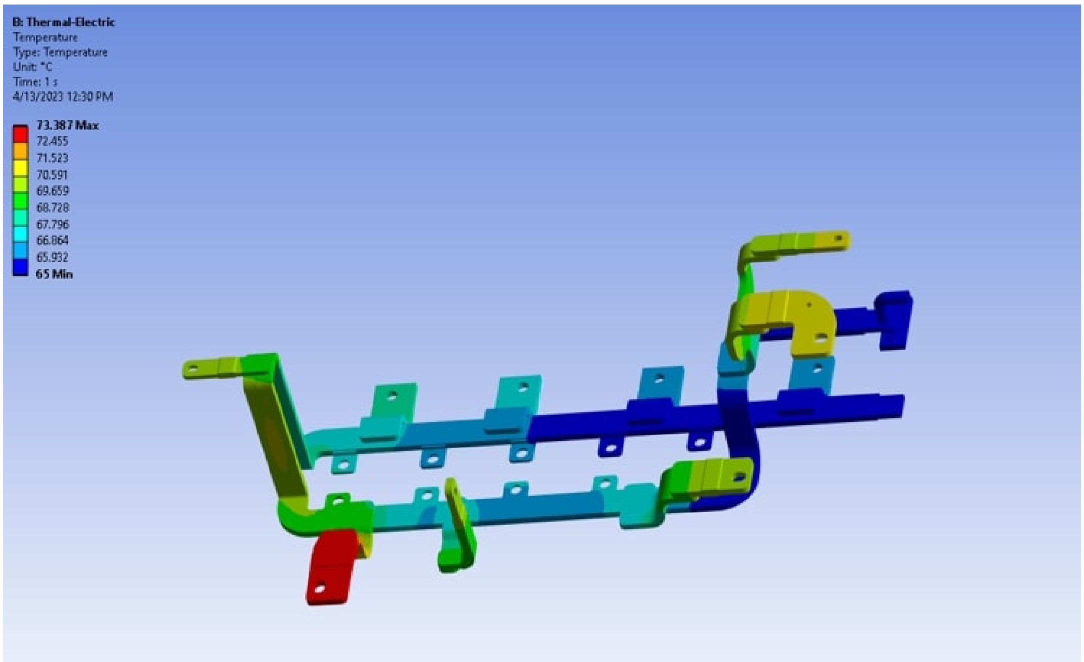

Figure 14: Thermal-Electric analysis of C Shape Busbar Design

It is worth noting that the hollow busbar design requires a larger cross-sectional surface area to accommodate the same electrical density as the C-shape design, particularly when dealing with DC currents as inputs to the busbars. In DC, the current flows uniformly throughout the cross-section of the conductor without significant concentration near the surface, as is the case with the skin effect in AC currents. Considering the challenges encountered with the hollow busbar and the alignment of the concept with the specifications of the thesis, the decision was made to proceed with further development and simulations of the C-shape design.

Although both the hollow and C-shape busbars exhibited the highest temperatures at ESS, the input port of the battery pack, the maximum temperature was significantly lower than the existing design, meeting the required specifications. Future cooling path modifications can be implemented to reduce the maximum temperature by shortening the laminar busbar and positioning the coolant closer to the ESS port.

6.6.4 Cross-Validation Using Excel Simulation Tool

An Excel simulation tool was developed to meet Volvo Trucks' requirements for calculating the busbar temperature accurately. The tool utilizes specific formulas outlined in section 2.5 and allows for inputting relevant parameters to obtain precise results. To ensure the accuracy of the calculations, the Excel tool performs cross-validation with ANSYS results.

Figure 15 illustrates that the busbar generates heat due to the high current flowing through it. Key input parameters for the busbar include thickness, height, and length. The total heat generation is calculated using the electrical resistivity of copper, which is $2.13 \times 10^{-8}\Omega \cdot \text{m}$. In the case of solid busbars, heat dissipation primarily occurs through the bottom surface by contact with the thermal interface material (TIM) layer. This allows heat to transfer to the aluminum wall, which is then cooled by the coolant. Therefore, heat conduction is the primary mode of heat dissipation for the bottom surface, while the remaining sides and top of the busbar experience heat diffusion through air convection. To simplify calculations, the TIM and aluminum housing are treated as composite materials with combined thickness and conductivity.

In the equilibrium state, the heat generation rate within the busbar is equal to the heat dissipation rate. The heat radiation from the copper busbar to its surroundings is considered negligible and is disregarded in the final heat calculation. The Excel sheet employs an equation as shown in equation 6.1 to estimate the maximum temperature of the busbar.

$$Q_{ge} = Q_{conv} + Q_{cond} \tag{6.1}$$

Here, Q_{ge} represents the joule heating, while Q_{conv} and Q_{cond} represent heat generated due to convection and conduction, respectively. This equation allows for estimating the maximum temperature reached by the busbar under the given conditions.

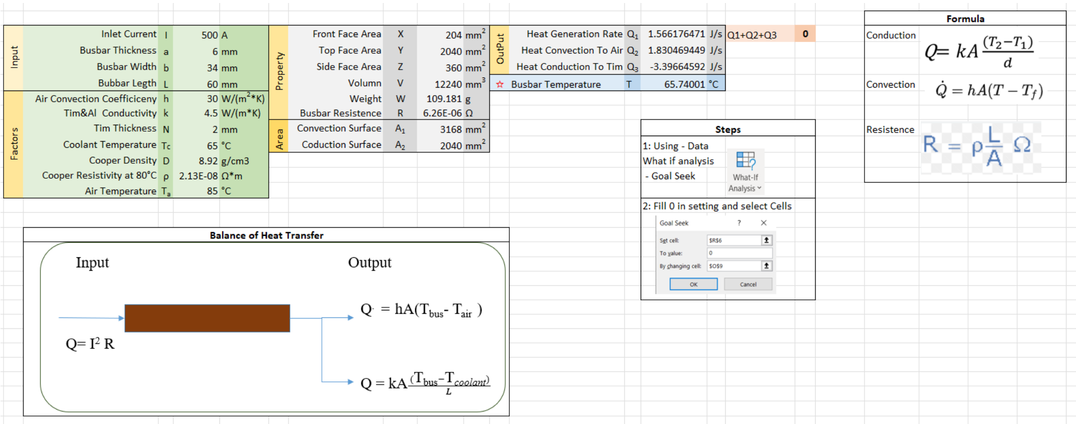

Figure 15: Excel Tool for Solid Busbar

Similarly, the same process is done for the C-shaped busbars. The only difference lies in calculating the conduction surface, which requires careful consideration due to the unique shape of the C-bar. Appendix G depicts a similar process and tool employed for the C shape busbar.

6.6.5 Conclusion

The proposed busbar cooling system's flexibility and excellent cooling efficiency are evident. The steady-state electric-thermal analysis provided valuable insights into the thermal behavior of different busbar designs under varying operating conditions. The hollow and C-shaped busbars demonstrated superior cooling performance compared to the existing layout, effectively reducing the maximum temperature at critical locations. However, the C shape busbar was chosen over the hollow busbar design due to the manufacturing and requirement constraints.

6.7 CFD analysis

Ensuring an appropriate pressure difference is crucial for achieving optimal cooling performance in the hollow tubes of the junction box. However, a separate pressure pump was not configured for this purpose to avoid negatively impacting the cooling performance of subsequent components. Therefore, a comprehensive CFD analysis was conducted to assess the pressure drop in the tube.

The coolant flow entering the junction box was set at 10.2 l/min. It was assumed that two coolant tubes, connected in series, were utilized to cool the positive and negative C-shape busbars. However, since the CAD models for the positive and negative busbars were identical, only the cooling system for the negative busbar, employing the C-shape design concept, was considered for the CFD analysis using ANSYS. The pipe's cross-sectional area associated with the C-shape busbar was approximately 135 square millimeters, resulting in an estimated flow velocity of 1.26 meters per second. This information was considered during the CFD analysis to evaluate the cooling performance accurately.

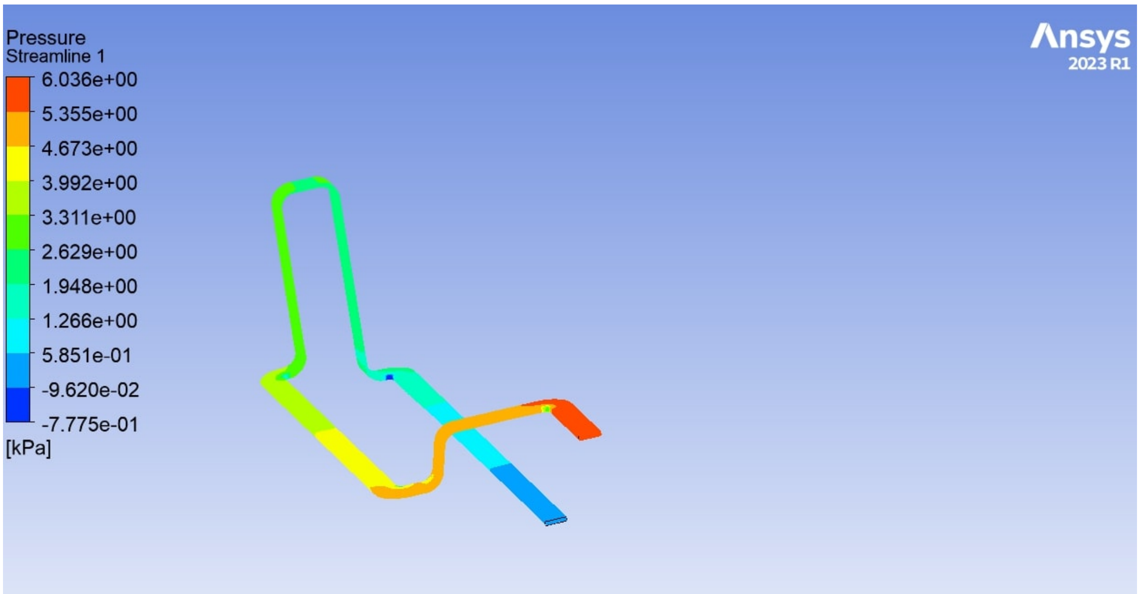

Figure 16: CFD Analysis for Pressure Drop in C Shape Coolant Tube

The iterative calculations utilized the appropriate dynamic parameters for the coolant, a water-glycol mix, at a temperature of 80 degrees Celsius. The analysis assumed no slip between the liquid coolant and the inner wall of the system. This assumption simplified the analysis process and reduced computation time by considering that the fluid in contact with the pipe wall had the same velocity as the wall, resulting in negligible slip velocity. This assumption was reasonable given the constant flow rate, smooth surface of the hollow coolant channel, and the Newtonian behavior of the coolant.

Based on these considerations, the analysis revealed a pressure drop of 6 kilopascals (kPa) between the inlet and outlet points, as shown in Fig 16. This pressure drop value was minimal, indicating the feasibility of the results obtained from the analysis. The minimal pressure drop suggested that the coolant flow through the hollow tubes of the junction box was effectively maintained, which was crucial for ensuring efficient cooling performance.

6.8 Correlation Between Parameters

As previously mentioned, the DoE method was utilized to analyze the relationships between the parameters in the study. While ANSYS provides a tabular representation of the parametric study results, visual graphs are considered more effective in enhancing understanding of these relationships and results. The Spyder software, a Python IDE (Integrated Development Environment), was employed to create visual plots and graphs. The general code for plot generation is listed in Appendix H.

Fig 17 represents the correlation between the maximum temperature and width of the busbar for a constant height of 6mm. The legend of the plot indicates the different thicknesses of the hollow cooling channel for the C shape busbar design.

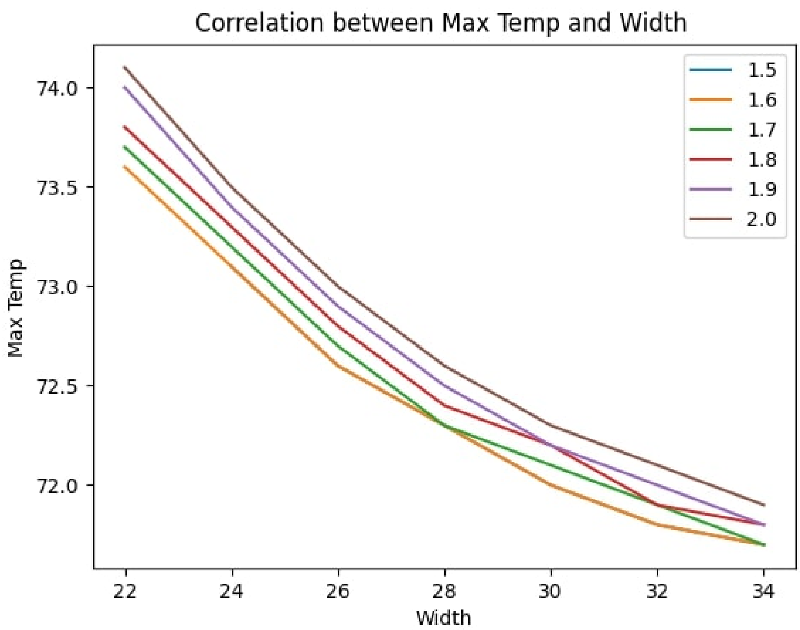

Figure 17: Correlation between Max Temp and Width

From the plot as well as DoE results, the following inferences are made:

- The weight of the busbar increases as the geometry parameters, especially the width, and height, are increased. This trend is in line with the engineering knowledge that more material attributes to the overall weight of the geometry.

- The maximum temperature of the busbar is inversely proportional to its width. As the width increases, the maximum temperature decreases. This relationship can be attributed to a wider busbar providing a larger surface area for cooling, allowing the coolant to dissipate heat more effectively.

- Similarly, the height of the busbar is inversely proportional to the maximum temperature generated. A greater height allows for a bigger hollow channel and a larger cross-sectional area for contacting coolant flow, thereby enhancing the cooling efficiency and lowering maximum temperatures.

- Based on the plot, it can be inferred that the optimal solution, considering both the maximum temperature and weight of the material as objectives, lies along the orange line since it was previously established that the width of the busbar mainly influences weight, a point on the orange line with a thickness of 1.6mm and a width greater than 28mm would result in the lowest maximum temperature generated.

6.9 Comparison: Final Concept vs Existing

Upon conducting extensive simulations, the final concept was compared against the existing busbar cooling design to validate the results and assess the feasibility and advantages of the proposed concept. Both models were subjected to the same simulation setup and boundary conditions, as discussed in subsection 6.6.2. The maximum temperature produced in the busbar while being cooled and the system's weight were crucial factors considered in this thesis. These analysis results served as metrics for comparing the two concepts. However, simulation results for the existing design were not included in this report due to confidentiality reasons, but they were discussed as target values.

- **Evaluation of maximum temperature:** As discussed earlier, the final concept achieved a maximum temperature of 73.4°C. This temperature is noticeably lower than when simulating the existing design under identical boundary conditions. The final concept successfully attained an 18.8% reduction in temperature compared to the existing design. This reduction holds significant value, especially in high-voltage power applications like EV junction boxes. The resulting final concept demonstrates its potential to meet the rigorous standards set by Volvo.

- **Evaluation of pressure drop:**The CFD analysis conducted on the final concept revealed a calculated pressure drop of 6 kPa. By Volvo Trucks' safety requirements, the burst pressure for the coolant pump was well over this value. Thus, the results obtained from the final concept remained well within the safety parameters defined by Volvo, showcasing superior performance compared to the existing cooling design. The lower pressure drop is accompanied by better cooling efficiency due to an improved heat transfer rate between the conducting surface and the coolant.

- **Weight Analysis:** The final concept incorporates two components: a C-shaped busbar made of copper and a coolant channel constructed from aluminum. The utilization of aluminum, which is lighter than copper, results in a substantial reduction in weight for the final concept, complemented by the implemented design changes. As a result, the final design achieves an impressive weight reduction of 45.5% compared to the existing busbar cooling system design. This weight reduction enhances overall system efficiency and offers advantages in terms of lower material cost compared to the existing busbar cooling system design. This weight reduction enhances overall system efficiency and offers advantages in terms of lower material cost.

Table 11 summarises the analysis results and comparison of the final concept against the existing design.

Table 11: Summary of Analysis Results

Design Parameter	Final Concept- C shape busbar
Material	Copper busbar and aluminium coolant channel
Max Temperature	73.4 $^0C(18.8\%reduction)$
Pressure Drop	6.03 kPa
Weight	45.4% reduction

6.10 Prototyping

After completing a meticulous series of computer-aided designs and validations, the project progressed to the final stage of product development: prototyping. The primary objective of this phase was to evaluate the feasibility of the design and present it as a conceptual demonstration. It is important to note that, at this stage, the prototype did not undergo extensive performance testing and validation. Therefore, the rapid prototype method of 3D printing was chosen.

By leveraging 3D printing technology, the design is transformed into a tangible prototype. This approach facilitates concept visualization, identifies potential challenges or shortcomings, and gathers crucial insights for further improvement. Although the prototype does not undergo comprehensive performance testing at this stage, it serves as a critical stepping stone toward developing a refined and successful final product.

The C-shaped busbar design was prototyped at Chalmers FUSE Labs using Polylactic acid (PLA) as the material. The model was scaled down to 75% to facilitate the printing process and printed in two parts: the C-shaped busbar and the coolant tube. For the post-processing of the C-shaped busbar, the bottom surface of the "C" was directly placed on the printer bed, minimizing the need for support material. The hollow tube, on the other hand, was laid flat on the printer bed for ease of printing since the internal supports did not affect its functional demonstration.

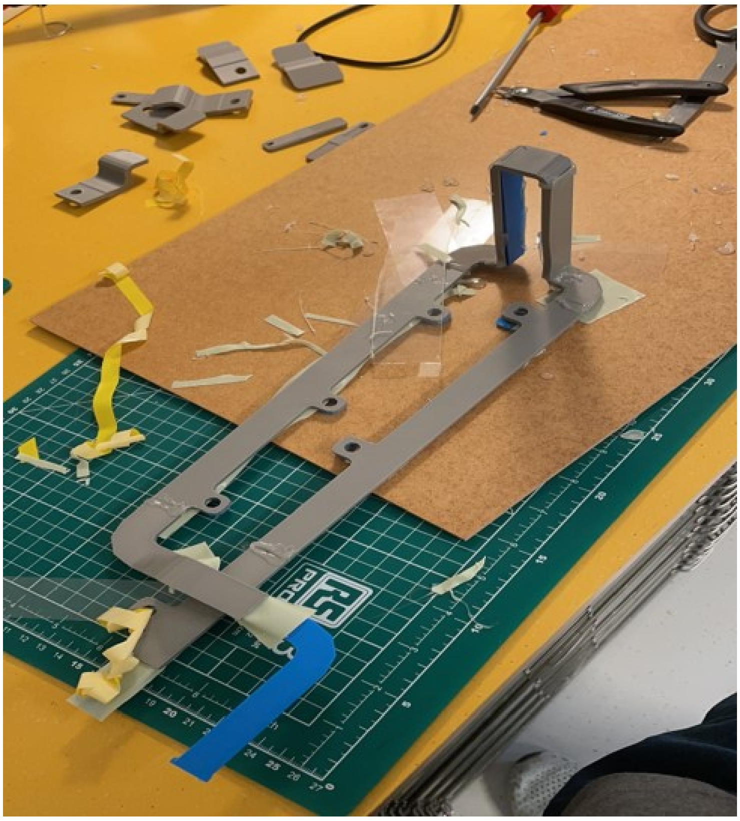

Figure 18: Prototype of C Shape Busbar

The model was 3D printed using PrusaSlicer, with a nozzle speed of 0.15mm and a 20% infill. After printing, the supports were carefully removed during the post-processing stage. The two components were then securely bonded using glue, with a layer of thermal interface material (TIM) applied between them to visually represent the structure of the model. The final prototype model, after post-processing, is depicted in Figure 18.

6.11 Fulfillment of requirements

After undergoing several iterative simulation processes, the maturely developed concept required an evaluation of the previously discussed specification requirements. Overall, the concept successfully fulfilled most of the requirements and desires. However, one specific requirement, namely *Low manufacturing cost*, could not be entirely met. The final concept, which involved the production of a new C-shape busbar, was anticipated to have higher machining costs than conventional solid busbars.

Nevertheless, this assumption can be reevaluated through a detailed cost analysis or mitigated by selecting an appropriate supplier for busbar production.

Regarding the desires related to the geometry of the busbar, such as *gap and flush*, they were not fully satisfied. However, these discrepancies can be easily addressed by modifying the CAD design to adhere to the strict requirements imposed by space constraints. The verification of the final concept against the product-specific requirements is illustrated in Table 12.

Table 12: Fulfillment of Requirement Specification

Requirement Specifications -Busbar Cooling Concept					
Criteria		**Sub-Criteria**	**R/D**	**Requirement**	**Fulfillment (Yes/No)**
Cost		Material cost	D1	Must be less than or equal to the existing material cost.	Yes
		Assembly cost	D2	Should have less or same cost to assembly than existing design.	Yes
Safety	Mechanical	Maximum temperature of busbar	R1	Must be lower than 85°C.	Yes
		Bending	R2	Should be stiff and have displacement less than 1 mm in Z direction.	Yes
		Intrusion	D1	Should have displacement less than 1 mm in Y direction.	Yes
		Stress	D3	Should be below the ultimate strength of chosen material.	Yes
	Electrical	Current capacity of busbar	R1	Must be capabable of effectively cool a peek current of 800A.	Yes
		Electrical insulation	R2	Must provide same or more safety than existing design.	Yes
	Material functionalities	Thermal conductivity	R1	Must have high thermal conductivity.	Yes
		Electrical resistance	R2	Must attend 800V electrical load as exisitng material.	Yes
		Corrosion resistant	D3	Should withstand corrosion.	Yes
Manufacturing	Manufacturability	Design for manufacturability	R1	Must be manufacturable easily.	Yes
		Manufacturing cost	R2	Must have low manufacturing cost.	No
	Assembly	Design for assembly	D1	Should be easily assemblable.	Yes
		No. of components	D2	Should have low number of components involved.	Yes
Weight		Cooling system	R1	Must be lower than existing design.	Yes
		Busbar	R2	Must be lower than existing design.	Yes
Geometry		Length and Width	R1	Must not exceed the battery housing dimensions.	Yes
		Gap and flush between busbars	R2	Must be less than 4 mm.	No
		Height	R3	Must be less than 10 mm.	No
Maintainability		Ease of repair	D1	Should be easy to repair.	Yes
		Ease of replacement	D2	Should be acceessbile and easy to replace.	Yes
Sustainability		Use of sustainable materials	D1	Should have lesser or equal CO2 emisison as existing design.	Yes
		Recyclable materials	D3	Should make use of recyclable materials.	Yes

7
Discussion

This chapter involves discussions and reflections about various methodology tools and studies performed in the thesis work.

7.1 Competitor Benchmarking

The thesis primarily focused on developing a cooling system for the busbar within the TVPDC box. The box, as discussed, is highly customizable depending on the requirements of the BEV manufacturers. As such, no valuable data was publicly sourced to enable a complete tear-down of the box employed by competitors. As a result, it was not possible to conduct a conclusive technological assessment and benchmarking between the solutions utilized by competitors and those used by Volvo Trucks. Most of the benchmarking data was obtained from literature studies about different material coatings on busbars. While websites like A2 mack1 [34] and Volvo Trucks' internal benchmarking reports were utilized, there were knowledge gaps between the benchmarked data of competitors such as Daimler, Scania, BYD, and Tesla Semi trucks. Hence there is scope for identifying new areas of improvement for busbar cooling based on inspirations drawn from extensive benchmarking of competitors' products.

7.2 Functional Analysis

Functional analysis is a crucial aspect of product development, serving as the foundation for subsequent stages like idea generation and prototyping. This thesis employed various functional analysis tools, including the black box model, process flow, function means, and function tree. While these methods yield positive outcomes, they can be complex and time-consuming to implement.

The function means tree is considered more effective than the function tree but has the drawback of limiting the solution space in the early stages of product development. However, the black box model and process flow were successfully used to understand the purpose and factors contributing to heating in the busbar. A well-constructed process flow chart can identify sub-functions, eliminating the need for a function tree.

It is worth noting that the function tree method was more time-consuming due to the need for extensive literature studies to address knowledge gaps. Nevertheless, the outcomes obtained were reliable and accurate.

7.3 Material Study

In the material study, different materials were benchmarked against the existing material used for the busbar based on data of material properties gathered mostly from CES EduPack. However, materials property data for some materials like CCA and PCM were quite challenging to investigate due to a lack of information. As such, although these materials were considered for the concept generation matrix, they were rejected from the final concept due to their difficulty in simulation with limited knowledge.

Similarly, difficulty was faced during evaluating CO_2 emission between the three final materials, copper, aluminium, and CCA. Concrete information about the primary production CO_2 emissions of CCA was lacking, which led to the assumption that CCA would have higher emissions than aluminum but lower emissions than copper. Additionally, it was assumed that the recycling CO_2 emissions of CCA would be higher than both copper and aluminum due to the increased energy required to separate the bonded copper and aluminum layers in CCA during the recycling process. These assumptions theoretically make sense but need to be backed by numerical and literature studies to validate their accuracy. Another important material property that could have been explored is corrosion and oxidation resistance, considering that metals, as excellent conductors of electricity, are more susceptible to corrosion compared to other materials.

The sustainability aspect of the material study was explored using only CO_2 emission during production and post-use. It would be interesting to have explored operational usage or energy density during production and the type of manufacturing process for the material. Operational usage has a significant amount of impact on electricity because the lightweight attribute of the material contributes to low energy.

7.4 Concept Development

The concept development phase utilized helpful methods such as morphological, elimination, Pugh, and Kesselring matrices, which provided a structured sequence from idea to concept. However, these matrices are time-consuming and require multiple revisions and careful planning to ensure diverse and accurate outcomes that meet the required specifications. Some concepts were innovative but deemed infeasible due to manufacturing constraints, highlighting the influence of design for manufacturing (DFM) knowledge on concept generation.

While splitting the sub-functions into two groups was practical, it may have overlooked concepts that involve combinations between different sub-functions and sub-solutions. Assessing knowledge gaps and interactions between sub-solutions requires time and evidence, especially in the case of the morphological matrix. Objective evaluation and elimination of combinations became challenging, revealing a drawback of the morphological matrix.

The elimination and Pugh matrices are suitable for initial concept assessment, but they are more effective when system-level interactions between sub-solutions are well-considered beforehand. Although efforts were made to analyze these interactions, some feasible combinations might have been deemed infeasible due to a lack of proper engineering knowledge and experience.

The Kesselring matrix considered weight, heat dissipation efficiency, and safety standards. However, striking a balance between these parameters posed challenges, with more emphasis on safety and heat dissipation efficiency to align with the thesis objective. Establishing appropriate weighting scales for each requirement required significant effort to account for their interdependence properly. Some criteria lacked numerical target values, leading to subjective evaluations based on safety and reliability compared to the existing solution. This subjectivity may have influenced the outcome of the Kesselring matrix.

7.5 Simulations

The thesis utilized non-linear static simulations in ANSYS software to evaluate the busbar's peak current and maximum temperature. However, dynamic simulations with varying load currents over time could have provided more concrete results. Initial attempts at dynamic thermal-electric simulation using ANSYS yielded poor results, but other simulation tools like Hypermesh and COMSOL Multiphysics could have been explored for better accuracy.

The simulation environment and boundary conditions for the final concepts and the existing design were the same, assuming the BEV was in motion over an extended period. Peak current from the ESS was specified as input, and current distribution to other ports was based on this current, determining the maximum temperature of the busbar. Although the thesis did not cover simulations during the charging phase, incorporating these simulations would have provided more comprehensive results and cross-validation of operational states.

CFD analysis was conducted to assess the pressure drop along the coolant path and validate against Volvo Trucks' values. Varying parameters such as flow rate, coolant temperature, coolant channel bend radius, and mesh sizes in the simulation environment would have generated more accurate results.

The thesis primarily focused on design parameters such as weight, material, maximum temperature, and stress. However, other aspects such as safety factors, crash analysis, durability, and Noise Vibration Harness (NVH) testing still needed to be addressed. The DoE was limited to 80 design points due to high computation time, considering busbar dimensions. Increasing the number of design points could have revealed new optimization possibilities in the Python correlation plots.

7.6 Final Concept

The final concept, the *C shape busbar*, outperforms the existing busbar cooling system in various aspects, as discussed in Chapter 6. However, specific challenges related to the manufacturability and efficiency of the U-shaped part of the design need to be addressed before implementing it in the TVPDC box. Despite these challenges, the final concept excels in performance, cost, and weight compared to the existing design, as it fulfills the requirements specified.

Direct cooling significantly reduces the maximum operating temperature, while using a C shape busbar and aluminum cooling tube reduces weight and cost. However, the machining cost of the C shape busbar may impact the overall design cost depending on its dimensions. The design and dimensions of the final concept are customized for the TVPDC box, but adjustments can be made for different box sizes using ANSYS. By parametrically changing dimensions, a new set of results can be observed.

A 3D-printed PLA prototype was used to test the practicality of the final concept. However, further exploration is needed to address complications that may arise when manufacturing metal parts. Additionally, the impact of electrical insulation safety measures and welding between the two components on the final concept's overall feasibility and cooling performance should be thoroughly investigated.

8
Conclusion

The chapter entails a conclusion of results obtained along with a revisit to the research questions.

The thesis aimed to develop an effective cooling system for busbars in the TVPDC box, consequently decreasing the busbar's operating temperature. A structured project development method was implemented in the thesis encompassing different stages from idea generation to prototyping and concept evaluation. The research questions posed in section 1.6 were successfully addressed as follows:

RQ1: How are the most optimal materials chosen for the coolant and the busbar regarding cost, performance, weight, and ease of replacement?

The thesis conducted an extensive material study to identify optimal materials for the coolant and busbar, considering cost, performance, weight, and ease of replacement. The study evaluated parameters such as thermal conductivity, electrical resistivity, strength-weight ratio, and sustainability to meet the objectives of weight reduction, cost efficiency, and temperature control.

RQ2: How can the maximum operating temperature of the busbar be reduced while being cooled simultaneously?

A thermal-electric analysis was performed to determine the maximum operating temperature of the busbar while ensuring effective cooling. The analysis considered the operation of a BEV, taking inputs from the battery storage and adjusting outputs based on current usage across other ports. CFD analysis was used to validate the design and ensure acceptable pressure drop in the truck.

RQ3: How can the busbar's dimensions be optimized to increase the current flow efficiency with minimal heat generated?

The thesis utilized DoE analysis and correlation plots to optimize the busbar's dimensions and increase current flow efficiency while minimizing heat generation. The DoE analysis explored various combinations of dimensions, identifying optimal configurations for maximizing current flow efficiency. The correlation plots visually represented the impact of busbar dimensions on performance, highlighting the importance of width, height, and thickness in reducing heat generation.

The conclusions drawn from the results are briefly discussed below.

- The material study indicates aluminium as a material alternative for e-mobility, offering affordability, reduced weight, and sustainability.

- The final design achieved an 18.8% reduction in the maximum operating temperature of the busbar while being cooled.

- The final design demonstrated a 45.4% weight reduction compared to the existing busbar cooling design, accompanied by decreased material costs.

- The correlation plots indicated that busbar width had the most significant impact on heat generation, followed by height and thickness. The optimal dimensions of busbars were a height of more than 5mm and a width greater than 24mm, accompanied by a minimum thickness of 1.6mm for efficient cooling.

- The final concept validated the potential of employing direct liquid cooling for busbars.

9

Future Work

This chapter discusses the recommended action plan for Volvo Trucks to improve upon the results obtained in the thesis study.

- Dynamic simulations with varying current loads on the busbars should be conducted to replicate real-world scenarios and obtain a more accurate temperature distribution graph over time. This will better understand the system's behavior under dynamic conditions.

- Similarly, the CFD analysis had a constant flow rate to evaluate the pressure drop across the inlet and outlet. However, to achieve more concrete results, different parameters need to be changed and assess the pressure drop, such as variable flow rate, ambient temperature, coolant temperature, and bend radius across the coolant path.

- Physical prototype testing is crucial to validate the simulation results and identify any potential issues that may arise during real-world operation. Volvo Trucks should prioritize prototype testing to ensure the proposed cooling system performs as expected and meets the required specifications.

- The feasibility of the concept design should be assessed by integrating it into the entire system and conducting testing in an actual working environment with appropriate parameters. This will provide insights into the system's performance, compatibility, and effectiveness.

- Further research and development are needed to improve the sealing technology and ensure effective electrical insulation on the coolant channel in the final concept. It is essential to ensure that the proposed solution is safe, reliable, and capable of preventing electrical hazards.

- The possibility and impact of welding between the C shape busbar and the coolant channel should be thoroughly investigated, followed by prototype testing. Vibration analysis can be conducted to obtain more comprehensive simulation results and assess the connection between these two components under operational conditions.

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A

Appendix - Requirement Specifications

Criteria		Sub-Criteria	R/D	Requirement	Set by	Evaluation/ Verification
Cost		Material cost	D1	Must be less than or equal to the existing material cost.	Volvo Trucks	CES Edupack
		Assembly cost	D2	Should have less or same cost to assembly than existing design.	Volvo Trucks	CES Edupack
Safety	Mechanical	Maximum temperature of busbar	R1	Must be lower than 85°C.	Volvo Trucks	Simulation
		Bending	R2	Should be stiff and have displacement less than 1 mm in Z direction.	Volvo Trucks	Simulation
		Intrusion	D1	Should have displacement less than 1 mm in Y direction.	Thesis Team	Simulation
		Stress	D3	Should be below the ultimate strength of chosen material.	Thesis Team	Simulation
	Electrical	Current capacity of busbar	R1	Must be capabable of effectively cool a peek current of 800A.	Volvo Trucks	Simulation
		Electrical insulation	R2	Must provide same or more safety than existing design.	Volvo Trucks	CES Edupack
	Material functionalities	Thermal conductivity	R1	Must have high thermal conductivity.	Volvo Trucks	CES Edupack
		Electrical resistance	R2	Must attend 800V electrical load as exisitng material.	Volvo Trucks	CES Edupack
		Corrosion resistant	D3	Should withstand corrosion.	Volvo Trucks	CES Edupack
Manufacturing	Manufacturability	Design for manufacturability	R1	Must be manufacturable easily.	Volvo Trucks	CES Edupack
		Manufacturing cost	R2	Must have low manufacturing cost.	Volvo Trucks	CES Edupack
	Assembly	Design for assembly	D1	Should be easily assemblable.	Thesis Team	Prototype
		No. of components	D2	Should have low number of components involved.	Thesis Team	Prototype
Weight		Cooling system	R1	Must be lower than existing design.	Volvo Trucks	CAD (Creo)
		Busbar	R2	Must be lower than existing design.	Volvo Trucks	CAD (Creo)
Geometry		Length and Width	R1	Must not exceed the battery housing dimensions.	Volvo Trucks	CAD (Creo)
		Gap and flush between busbars	R2	Must be less than 4 mm.	Volvo Trucks	CAD (Creo)
		Height	R3	Must be less than 10 mm.	Volvo Trucks	CAD (Creo)
Maintainability		Ease of repair	D1	Should be easy to repair.	Thesis Team	Prototype
		Ease of replacement	D2	Should be acceessbile and easy to replace.	Thesis Team	Prototype
Sustainability		Use of sustainable materials	D1	Should have lesser or equal CO2 emisison as existing design.	Thesis Team	CES Edupack
		Recyclable materials	D3	Should make use of recyclable materials.	Thesis Team	CES Edupack

Figure A.1: Requirement Specification List

B

Appendix - Materials Benchmarking

Table B.1: Material Benchmarking Using Reference Material

Material	Price (SEK/kg)	Density (kg/m3)	Young's Modulus (Gpa)	Thermal Conductivity (W/ m oC)	Max Service Temp (o C)	Electrical Resistivity (µ ohm.cm)	Primary production CO_2 emissions (kg/kg)
copper, C10500, hard (Ref)	52	8950	135	385	250	1.7	6.41
copper, C12200, hard	54	8950	135	360	200	1.91	6.41
Copper, C12500, soft	53.8	8950	125	372	150	1.82	6.85
Copper,14200,soft	53.6	8950	125	186	140	3.8	6.52
Al ,6063,O	23	2720	80	225	180	2.93	13.2
Al,5052, O	23	2720	75	150	150	4.8	13.4
Al, 665, T5	23	2720	70	185	150	3.44	13.2
Al, 6063, T6	24.2	2720	73	205	140	3.2	13.2
Brass, CuZn10, C2200, soft	54	8800	125	190	200	3.98	6.75

Table B.2: Material Benchmarking Using CES Edupack

Material	Price (SEK/kg)	Density (kg/m3)	Young's Modulus (Gpa)	Thermal Conductivity (W/ m oC)	Max Service Temp (o C)	Electrical Resistivity (µ ohm.cm)	Primary production CO_2 emissions (kg/kg)
Brass, C67500, hard	48	8940	110	106	225	6.97	5.83
Brass, Cuzn38Mn1.5,	46.4	8360	103	125	110	7.59	5.8
Magnesium, Elektron	60.3	1810	45	120	180	9.3	9.85
Magnesium,Z6	30	1840	47	125	180	5.37	18.85
Magnesium, ZC71	31.8	1840	44	120	130	5.5	9.72
Magneisum, ZK601-7	29.6	1830	45	125	130	5.37	9.85
Zn-Al alloy (85-15)	26.6	5930	90	125	100	5.4	5.4
Zn-copper alloy, work	28.3	7200	90	115	100	5.8	3.98
Zn-Cu-Mg alloy, Z45	28.1	7190	80	105	110	6.2	3.93
Zn-cu-Ti alloy	28	7100	105	110	100	5.8	3.59

C
Appendix - TRIZ Based Design

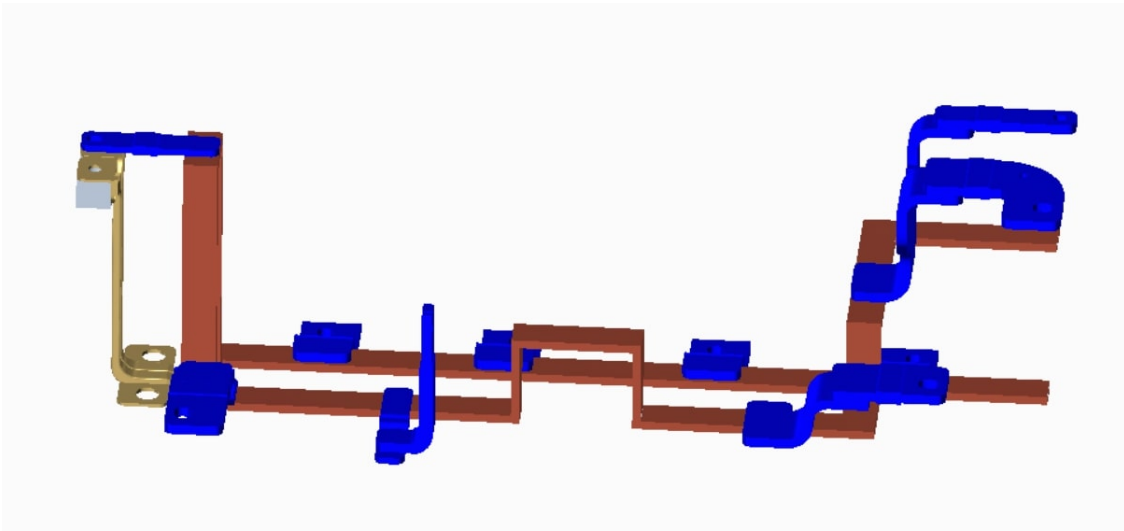

Figure C.1: Heat Pipe design inspired from TRIZ method

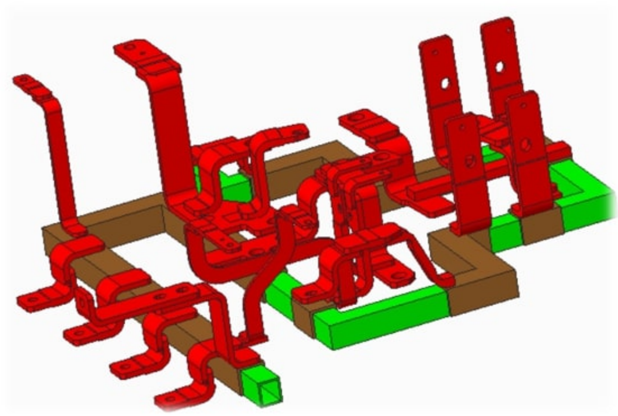

Figure C.2: Modular busbar design inspired from TRIZ method

D

Appendix - Idea Generation Morphological Matrix

Table D.1: Idea Generation Morphological Matrix

Sub-function	Base Concepts Ideas					
	1	2	3	4	5	6
F1: Specify main busbar	Solid busbars	Hollow busbars	Laminar Busbars	C- shape busbars	Combination	
F2: Specify branch busbar	Laminar	Solid	Hollow	Combination		
F3: Heat- dissipating structures	Fins	Hollow tube	Heat Pipe	Heat exchanger and sink	Holes	
F4: Mount components	Bolts	Clamps	Welding	Combination		
F5:Optimize cross-section	Square	Rectangle	Circular	Square with rounded corners	Rectangle with rounded corners	combination
F6: Enable servicing	Same components	Different components	Modular design	Serviceable parts outside the battery housing		
F7: Provide thermal Insulation	Phase change material (PCMs)	Thermal Insulating material (TIM)	Insulation coating of busbars on the inside	Use of Foam material	Use of film material	Insulation coating on the outside of busbars
F8: Place cooling channel	Inside the housing	Underneath the housing	Along the sides of housing	Through the busbars	Along the busbar	Both on inside and outside housing
F9: Configure cooling channels	None	One	Two	More than Two		
F10: Ensure coolant recylcability	Cooling channel conncetion from intlet to outlet	Cooling chanel outlet to resorvoir and to cooling container	Use of filter to recycle the coolant impurities			
F11: Provide electrical Insulatior	Plastic coolant tube	Insulation material on inside of tube	Insulation material on outside of tube			
F12: Cooling method	Direct Cooling using Liquid	Indirect cooling using liquid	Air cooling using fans	Natural convection using air	Liquid and air cooling	Heat Pipe
F13: Heat Dissipating material	Copper (Cu)	Aluminium (Al)	Copper Clad Aluminium			

E

Appendix- Full Concept Morphological Matrix

Table E.1: Full Concept Morphological Matrix 1-5 Concepts

Sub-function		Total Concept Solutions				
		C1	C2	C3	C4	C5
Critical sub functions	F1: Specify main busbar	Solid busbars	Hollow	Hollow	Solid	Hollow
	F2: Specify branch busbar	Laminar	Laminar	Solid	Hollow	hollow
	F3: Heat- dissipating structures	Hollow tube	coolant	Hollow tube	Holes and fins	Coolant and holes
	F5: Optimize cross-section	Rectangle	Inner and hollow cross-section are rectangle rectangle	Rectangle on inner and outer area of hollow square	Outer area rectangle and inner hollow square	Inner and hollow cross-section are rectangle
	F8:Place cooling channel	along the housing	Underneath the housing	Underneath the housing	Through the busbars	Through the busbars
	F9: Configure cooling channels	one	one	More than two	one	Two
	F12: Cooling method	Indirect Cooling using Liquid	Indirect cooling using liquid	Indirect cooling using liquid	Direct cooling using liquid	Direct cooling using liquid
	F13: Heat Dissipating material	Copper (Cu)	Copper (Cu)	Copper (Cu)	Copper (Cu)	Copper Clad Aluminium (CCA)
Supporting sub functions	F4: Mount components	Welding	Welding	Welding	Welding and Bolts	Welding
	F6: Enable servicing	Same components	Different Components	Different Components	Different Components	Same components
	F7: Provide thermal Insulation	Phase change material (PCMs)	Insulation coating of busbars on the outside	Insulation coating of busbars on the outside	Use of film material	Phase change material (PCMs)
	F10: Ensure coolant recylcability	Cooling channel connection from intlet to outlet	Cooling channel outlet to resorvoir and to cooling container	Cooling channel outlet to resorvoir and to cooling container	Cooling channel conncetion from intlet to outlet	Cooling channel connection from intlet to outlet
	F11: Provide electrical Insulation	Plastic coolant tube	Insulation material on inside of coolant path	Insulation material on outside of coolant path	Insulation material on inside of coolant path	Plastic coolant tube

Table E.2: Full Concept Morphological Matrix 5-10 Concepts

Sub-function		Total Concept Solutions				
		C6	C7	C8 (existing)	C9	C10
Critical sub functions	F1: Specify main busbar	C- shape busbars	C- shape busbars	Solid busbars	Hollow	Solid
	F2: Specify branch busbar	solid	Laminar	Laminar	Laminar	Hollow
	F3: Heat- dissipating structures	Coolant and fins	Coolant	Coolant	Coolant	Coolant
	F5: Optimize cross-section	Busbar has C cross-section and coolant rectangular	Busbar has C cross-section and coolant rectangular	Rectangle	Rectangle hollow structure	Recantagle and square hollow busbar
	F8:Place cooling channel	Inside the housing	through the busbars	Underneath the housing	through the busbars	Inside and Underneath the housing
	F9: Configure cooling channels	Two	Two	One	Two	Two
	F12: Cooling method	Indirect cooling using liquid	Direct liquid cooling and natural air convection	Indirect cooling using liquid	Direct liquid cooling and natural air convection	Indirect cooling using liquid
	F13: Heat Dissipating material	Copper (Cu)	Copper (Cu) and Aluminium	Copper (Cu)	Copper (Cu)	Al main busbar and Cu branch busbar
Supporting sub functions	F4: Mount components	Welding and Bolts	Welding and Bolts	Welding and Bolts	Welding and Bolts	Welding and Clamps
	F6: Enable servicing	Different Components	Different Components	Different Components	Same components	Same components
	F7: Provide thermal Insulation	Thermal Insulating material (TIM)	Thermal Insulating material (TIM)	Thermal Insulating material (TIM)	Thermal Insulating material (TIM)	Insulation coating of busbars on the outside
	F10: Ensure coolant recylcability	Cooling channel outlet to resorvoir and to cooling container	Cooling channel outlet to resorvoir and to cooling container	Cooling channel outlet to resorvoir and to cooling container	Cooling channel conncetion from intlet to outlet	Cooling channel connection from intlet to outlet
	F11: Provide electrical Insulation	Plastic coolant tube	Insulation material on outside of coolant path	Insulation material on outside of coolant path	Insulation material on inside of coolant path	Plastic coolant tube

F

Appendix - Kesselring Weighting Scales

Cooling method efficiency	
Value	Grade
Performance	
Least efficient	1
Less efficient	2
Same as existing	3
More efficient	4
Most efficient	5

Electrical insulation safety	
Value	Grade
Reliability	
Very unreliable	1
Unreliable	2
Acceptable	3
Reliable	4
Very reliable	5

Use same exchangeable parts as currently used	
Value	Grade
% of exchangeable parts	
20%	1
40%	2
60%	3
80%	4
100%	5

Design should weigh low	
Value	Grade
kg	
> 8	1
6-8	2
4-6	3
2-4	4
< 2	5

Heat dissipation efficiency	
Value	Grade
Performance	
Least efficient	1
Less efficient	2
Same as existing	3
More efficient	4
Most efficient	5

Requirement of new supporting modules	
Value	Grade
Number of systems to be modified	
>4	1
3-4	2
2-3	3
1-2	4
<1	5

Design should be compact	
Value	Grade
Area Covererd in m2	
>3	1
2,5-3	2
2-2,5	3
1,5-2	4
<1,5	5

Stiffness less than 1mm in Z direction	
Value	Grade
Reliability	
Very unrealiable	1
Unreliable	2
Acceptable	3
Very reliable	4
Reliable	5

Current carrying capacity	
Value	Grade
Performance	
Least efficient	1
Less efficient	2
Same as existing	3
More efficient	4
Most efficient	5

Should be easy to assemble	
Value	Grade
Performance	
Very hard	1
Hard	2
Acceptable	3
Easy	4
Very easy	5

Should be easy to manufacture	
Value	Grade
Performance	
Very hard	1
Hard	2
Acceptable	3
Easy	4
Very easy	5

Figure F.1: Kesselring Weighting Scales

G

Appendix -Excel Simulation Tool for C Shape Busbar

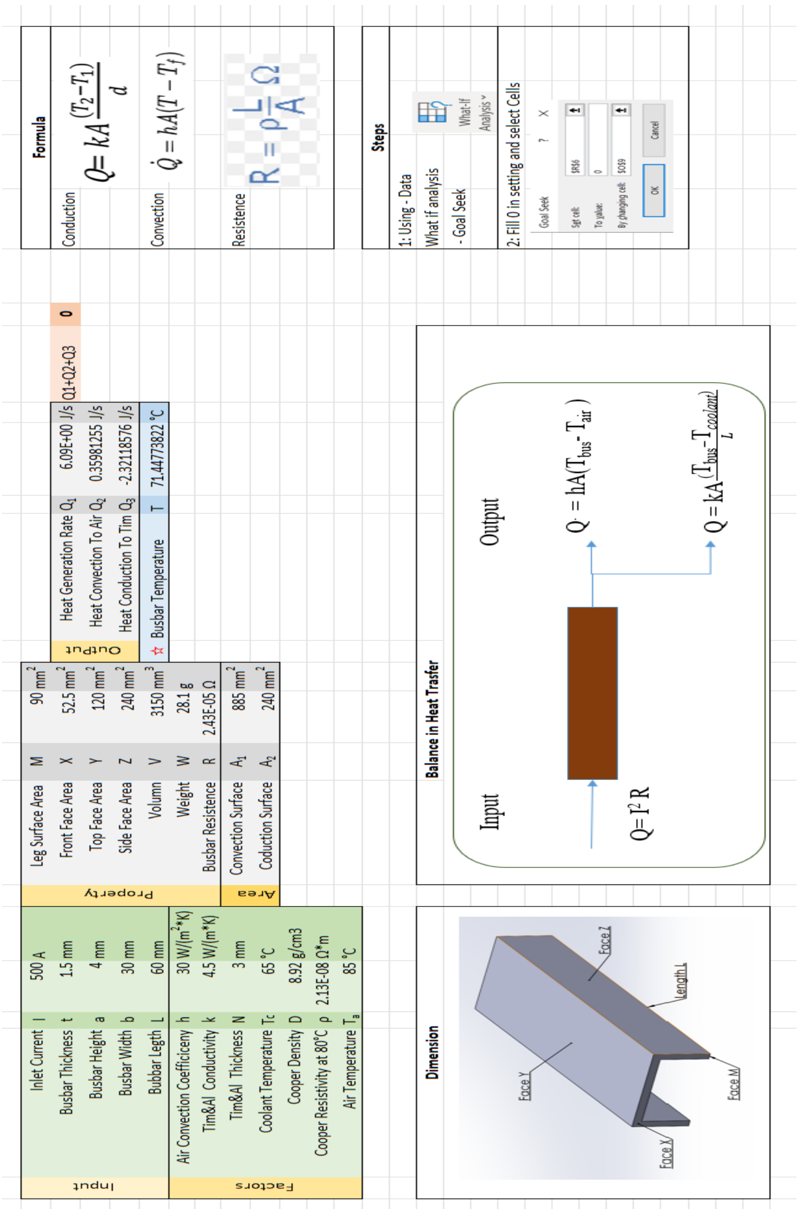

Figure G.1: Excel Simulation Tool - C shape Busbar

H

Appendix - Python Code for Plot Generation

```
# -*- coding: utf-8 -*-
"""
Spyder Editor

This is a temporary script file.
"""
from mpl_toolkits import mplot3d
import numpy as np
import matplotlib.pyplot as plt

import pandas as pd

data = pd.read_csv('file location')

z = data['P4']
x = data['P3']
y = data['P1']

fig = plt.figure(figsize=(10, 7))
ax = plt.axes(projection="3d")
ax.scatter3D(x, y, z, color="green")
plt.title("simple 3D scatter plot")
xLabel = ax.set_xlabel('Width', linespacing=3.2)
yLabel = ax.set_ylabel('Thickness', linespacing=3.1)
zLabel = ax.set_zlabel('Max temp', linespacing=3.4)
plt.show()

# read the data from the CSV file
data = pd.read_csv('file location')

# create the figure and axes
fig, ax = plt.subplots()

# plot the data
for name, group in data.groupby('P3'):
    ax.plot(group['P1'], group['P4'], label=name)
    yLabel = ax.set_ylabel('Max Temp', linespacing=3.1)
    xLabel = ax.set_xlabel('Thickness', linespacing=3.2)
    plt.title("Correlation between Max Temp and Thickness ")
# add a legend
ax.legend()

```

```
# show the plot
plt.show()

fig, ax = plt.subplots()

# plot the data
for name, group in data.groupby('P1'):
    ax.plot(group['P3'], group['P4'], label=name)
    yLabel = ax.set_ylabel('Max Temp', linespacing=3.1)
    xLabel = ax.set_xlabel('Width', linespacing=3.2)
    plt.title("Correlation between Max Temp and Width ")
# add a legend
ax.legend()

# show the plot
plt.show()
```

Listing H.1: Python code example

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