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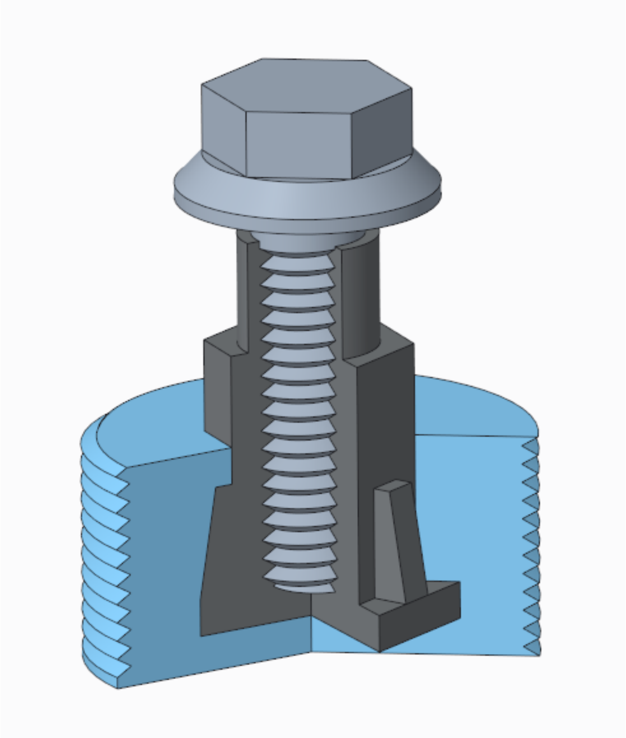

Investigation of Busbar Fixation for Commercial Electric Vehicle Power Distribution Unit

Final Report Draft

Master's thesis in Product Development and Mobility Engineering

Åke Sterning and Maulik Rakesh Rajput

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

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Investigation of Busbar Fixation for Commercial Electric Vehicle Power Distribution Unit
Final Report

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Cover: CAD model image of the final concept for the busbar fixation solution

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Abstract

In recent years, the trucking industry has been steadily progressing toward electrification, opening new avenues for innovation and development. A key component in this transition is the Power Distribution Unit (PDU), which plays a vital role in distributing and monitoring electrical power from the battery packs to various vehicle systems while ensuring protection against short circuits.

This thesis focuses on the development of new concepts for the busbar fixation catalogue within the PDU. Busbars are conductive elements that must be both securely fixed and electrically insulated from the surrounding conductive housing. The fixation solutions must meet stringent mechanical, thermal, and electrical requirements to ensure product robustness, safety, and compliance with industry standards.

The project follows a structured product development process with an emphasis on mechanical design. While customer requirements were generalized for company secrecy and to foster broader innovation, the scope was narrowed to solutions that are both space-efficient and cost-effective. A concept generation phase was conducted, resulting in multiple sub-solutions addressing the various functional demands of busbar fixation.

These concepts were systematically evaluated using selection matrices based on criteria such as assembly efficiency, material cost, manufacturability, and overall performance. Three final concepts were selected for further analysis, each offering a distinct approach to fulfilling the core functional requirements.

A detailed design phase followed, incorporating material selection, 3D CAD modeling, and computer-aided engineering (CAE) simulations. Special attention was given to ensuring the design met load-bearing and insulation requirements. A static structural analysis was performed to verify the chosen solution under maximum expected load conditions. Throughout the project, iterative evaluations and design refinements were carried out to ensure the quality and feasibility of the final concept.

Keywords: Busbar, Fixation, High Voltage, TVPDC, Electromobility, Power supply distribution unit

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Åke Sterning and Maulik Rakesh Rajput, Gothenburg, June 2025

List of Acronyms

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

AC	Alternating current
BEV	Battery Electric Vehicle
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CTI	Comparative Tracking Index
DC	Direct current
DFA	Design for Assembly
DFM	Design for Manufacturing
EMOB/Emob	Electromobility
EV	Electric Vehicle
FEM	Finite Element Method
HV	High-voltage
ICE	Internal Combustion Engine
PDU	Power Distribution Unit
SBCE	Set-Based Concurrent Engineering
TIM	Thermal Interface Material
TVSD	Traction Voltage Supply Distribution
TVPDC	Traction Voltage Power Distribution Center
TVSD	Traction Voltage Supply Distribution
Volvo GTO	Volvo Group Trucks Operations
Volvo GTT	Volvo Group Trucks Technology

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Introduction

The introduction chapter describes the background of the project and establishes its objectives, goals, and research questions, which form the basis of the study. It also delineates the scope and delimitations of the project, along with a summary of the report structure.

1.1 Background

Volvo Trucks is a world-leading truck manufacturer committed to their core values of quality, safety, and environmental care. With an estimated 134.000 trucks delivered in 2024 and more than 1.000.000 trucks in active service (“About Us”, 2025), they have a great effect and an opportunity to change the world for the better.

To meet the ambitions of the Paris Agreement ((COP21), 2015), in part by eliminating the use of fossil fuels and, thus halting global warming, a step for Volvo has been to electrify trucks, improving urban lives by reducing air and noise pollution (2019).

Figure 1.1: The Volvo Group pathway to decarbonization (2019). Credit: *Volvo Group.*

The target for *Volvo Group* is to have 35% of total sales consisting of electrical vehicles by 2030.

Taking into account the volumes of sales, the objectives and core values presented, *Volvo's* electrical trucks are faced with tough requirements from legislation, the *Volvo* organisation itself, and its users. While adhering to creating value for shareholders, the path forward must be precisely balanced between caring for the environment, customers, and generating value for other stakeholders. Keeping efficiency while consistently delivering volumes of around 134.000 trucks per year is difficult, and while internal combustion engine (ICE) trucks have been optimised for over 100 years (2021), electric trucks are young in relative terms. This puts pressure on the components of the electrical truck to be equally reliable and efficient.

Volvo delivered its first electric truck in February 2019 (Volvo Trucks, 2019) with a clear focus on early-to-market. In the centre of the electrical truck, the *Traction Voltage Supply Distribution Center, TVPDC,* controls and supplies the electrical components of the truck with electricity. The *TVPDC* used today is the first (in-house developed) traction voltage junction box at *Volvo Electromobility, Emob.* Due to this newly developed component/technology, the solutions might not have been optimal as they were overlooked to swiftly reach the objective.

Reducing emissions from the transportation industry is essential for a sustainable future. To realise this goal, one of the current solutions in the 2025 mobility sector is to eliminate the use and emissions of fossil fuels and products, gradually shifting the industry from a majority of internal combustion engine vehicles to electric and/or hydrogen power. A major actor in this transition is the Electromobility Division of *Volvo Trucks*. In addition, in the heart of electrical trucks, the *Traction Voltage Power Distribution Center* is a vital component for the vehicle's function and thereby ensures that the logistics and services that keep society running are functioning well. To guarantee this, every component of the truck must be robust, reliable, and safe.

The current TVPDC features various electrical components and high voltage cables that connect them, i.e. *busbars*. These components and busbars are connected and fixed to the housing by several independent fixation points that are spread throughout the unit, creating an intricate assembly that connects various parts of the busbars at different locations in the enclosure. In addition, the component itself has inherent areas of improvement, as it was initially developed with a primary focus on functionality and, to a lesser extent, optimisation. As a result, it might not fully adhere to all principles, making some processes tedious and time-consuming, or non-optimised.

Additionally, the existing busbar layout and fixation locations further complicate assembly by restricting accessibility. To address these challenges, there is a need for a thorough evaluation of the design of the fixation method that considers the necessary constraints and provides recommendations for design improvements, i.e., this project. If done thoroughly, this increases the probability of finding and perchance implementing a superior solution compared to the current one in terms of assembly, packaging, cost, and performance.

1.2 Objectives and Aim of Thesis

The purpose of the project is to investigate and provide recommendations for new fixation concepts for *Volvo Electromobility*. This will be done by evaluating and assessing the current solution's implications, and what can be learnt from them. These learnings will be further analysed and used in the systematic product development approach described in Section 3. The new concepts will be analysed, evaluated, and constructed using CAE for concept presentation at *Volvo* for feedback before final adjustments and optimisation work.

The output concepts will be met with revised requirements that reflect market standards or more. The final concept or concepts will be presented in the internal report along with the authors' recommendations to provide knowledge about busbar fixation for *Volvo*. In addition to this, the objectives to be fulfilled are listed below;

- Identify and suggest areas of improvement in product design by investigating and understanding the issues related to the current solution.
- Demonstrate the iterative nature of a product development chain with the approach of designing, analysing, optimising, and potentially prototyping & testing.
- Simulate and analyse the performance of the generated concept recommendations using Computer Aided Engineering (CAE) tools to provide recommendations for *Volvo*.

- Evaluate and provide answers to the research questions.

In addition to technical objectives, the project also promotes social, ethical and ecological values (“Volvo Sustainability Goals”, 2015). Each phase of the project adheres to *Chalmers* code of conduct and *Volvo* standards and relevant regulations throughout the design and manufacturing processes. This ensures the well-being not only of the creators, but also of consumers and the environment. Furthermore, supporting the decision to transition to electric trucking infrastructure contributes to a greener future and a sustainable society.

1.3 Research Questions

The thesis objectives in the initial period of the project are to extract and answer the following research questions (RQ’s).

1. What improvement opportunities/characteristics can be identified in the current busbar fixation solution that affect overall performance and efficiency?
2. How can a new/updated design solution be formulated to improve performance on the findings of RQ1?
3. What are the advantages and remaining challenges and what can be recommended for further work?

1.4 Project Context

When generating new concepts, the design engineer draws inspiration from anything the individual feels can contribute to the outcome of the final concepts. In some contexts, this can be from already existing solutions or sub-solutions that are then modified to the specific purpose of the task at hand. The customer commonly sets the focal point or objective with the new concept generation to improve an area that is non-optimised, this could be for example to reduce the number of parts in the final product, how they are produced or how they are assembled, this translates to designing for manufacturing, DFM, and designing for assembly, DFA. In accordance with *TVSD* department, this project focusses on generating new, innovative concepts.

The scope of the project is delimited to sector 4 in Figure 1.2

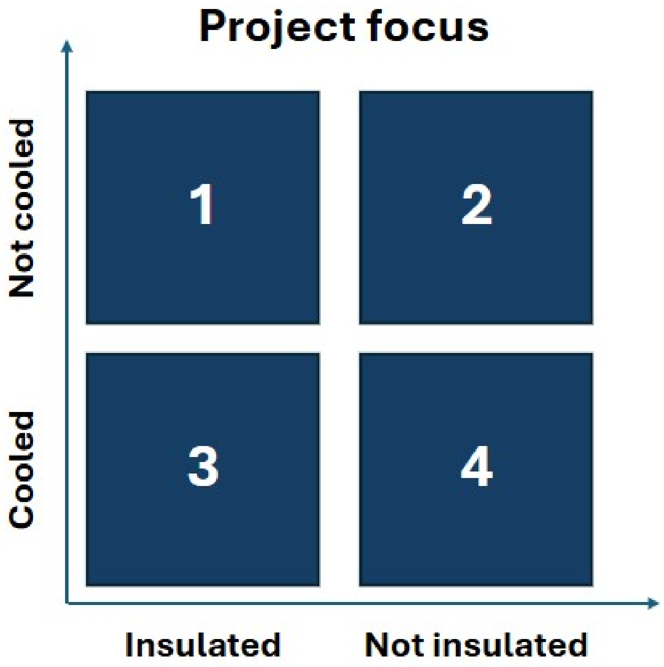


Figure 1.2: Project focus matrix.

During the initial phase of the project, the scope of the project was narrowed to investigate fixation solutions for actively cooled, non-insulated busbars, as this puts tougher electrical requirements on the fixation solution. The decision was made to allow the project to faster focus on investigate detailed solutions and thereby faster suggesting qualitative concepts.

1.5 Delimitations

The project seeks to generate and iterate new concepts for busbar fixation methods in the use and context of *Volvo*. This does not necessarily mean that it will be used exclusively in the TVPDC; however, given the involvement of the TVSD department in the project and the expertise of the working colleagues, the TVPDC will be used as a benchmark to solve the task of the fixation method. The automotive industry is commonly constrained by packaging and cost etc., this entices delimiting cost- and volume-inefficient concepts.

To generate a reproducible result and reduce bias, the thesis uses a structured and data-driven method. The methodology will mainly comprise the structure suggested by (Ulrich et al., 2011a) *Product Design and Development* and is the taught and recommended approach in the Chalmers product development masters programme. Other methods, such as the *Design Build Test-method* (DBT) can yield valuable results, however in a thesis and research context, this method does not provide structure for the extensive documentation needed for producing a reproducible result. Further, DBT might require facilities unavailable to the project given the need of prototyping. Therefore, the thesis delimits to using the recommended approach. More delimitations are presented below:

- The project is constrained within *Chalmers* spring semester of 2025, that is, from January 20th to June 8th.
- As some information and data is proprietary to *Volvo*, only information approved by *Volvo* will be included in the public version of this report.
- The thesis has access to *Chalmers* and *Volvo* facilities, resources, and tools, together with an unspecified budget.
- The investigation assumes the demand for the product and project; therefore, *opportunity identification* part of the book methodology is excluded (Ulrich et al., 2011a).
- The main emphasis of this thesis is to develop recommendations for busbar fixation methods, particularly for the commercial automotive industry.
- The fixation method developed in this thesis is primarily intended for TVPDC-like power distribution units as a reference/benchmark but will also aim to address other relevant use cases within this domain.
- The investigation is limited to analysing, assessing and evaluating concepts given the time scope of the project, unless time allows further development of prototypes and testing.

1.6 Report Outline

The purpose of the outline of the report is to briefly introduce the reader to how and why the report is constructed as it is.
The Introduction chapter is meant to provide context to the problem aligns with the thesis and *Volvo's* vision and core values. It also presents the project task and how it has been decomposed into objectives and research questions.
Theory provides knowledge of the information necessary to understand the inputs to the process and how the results emerged.
The Methods section shed light on the product development methodology for the thesis, the process is used to systematically generate concepts and terminate concepts that are objectively inferior. The systematic approach allows for reproduction of the development process and reduces the risk of bias.
The Results section consists of the outputs generated at each step of the methodology, along with a reflection of how they were achieved. This section also discusses the final concepts and how they are superior to the current solution.
Conclusion provides suggestions for *Volvo* along with answers to research questions.
The Discussion elaborates perspectives and nuances to the results and conclusion and mentions the authors' view on possible future investigations or complementary actions for this project.

2

Theory

The trend in the automotive and commercial automotive industry is moving towards higher battery voltage use, from the conventional 400 V to 800 V or 1200 V and more (2024)(2022)("Understanding Voltage and Current in Electric Car Batteries: Key Insights for Charging", 2025). This indicates a changing environment where modular solutions are beneficial. From the formula $power = voltage * current$, or $P = UI$, this voltage increase means more efficient motors, faster charging, and longer range, which are desirable factors (2025)(n.d.). Research by (Rizzoli et al., 2022) shows that an increase from 400 V to 800 V can reduce the charging time by an estimated 30%. The theory chapter contains information that is vital to understanding the research and development of the final concepts. Further, how busbars, TIM, fixation, material characteristics, and other information are presented is important to understand why the components must meet the requirements of the truck.

2.1 General Knowledge

Of the different sub-systems mentioned from the TVPDC, some might not be familiar to everyone. Castings and fixations are common objects to engineers, however busbars and thermal interface materials (TIM) are more niche toward electrical contexts and industries. This section aims at introducing and providing context for these sub-systems.

2.1.1 Busbars

Busbars are metallic electrical conductors that are typically used for general HV distribution applications where they carry high currents from the source to the desired component. In this case, busbars are used in high voltage junction boxes of electric trucks.

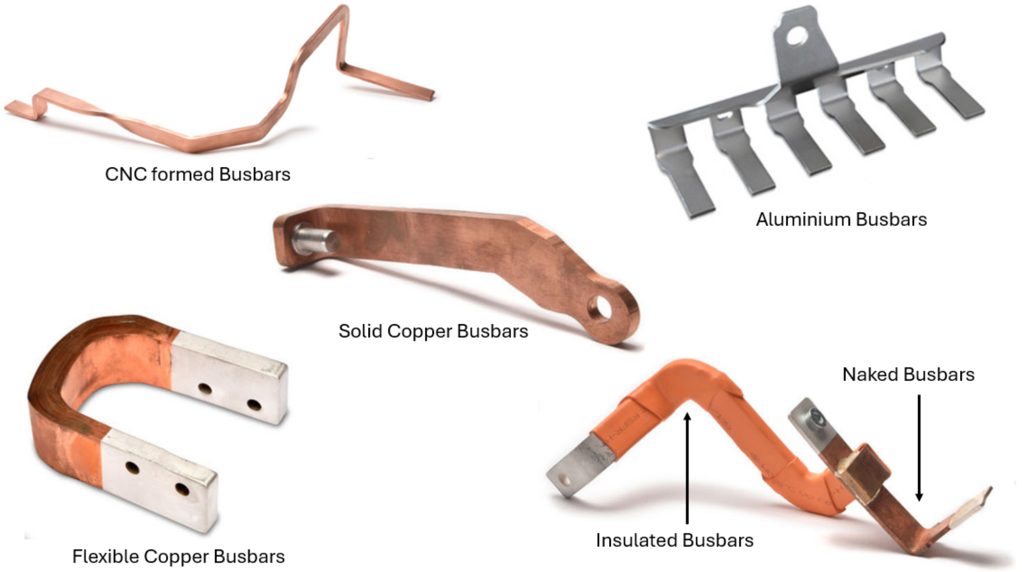


Figure 2.1: Various types of busbars

As seen in Figure 2.1 (Connor Manufacturing, n.d), they can be of various shapes, sizes, and materials and therefore vary depending on the requirements. In the automotive industry context, they can be classified as aluminium or copper busbars. Furthermore, they can be either solid or flexible depending on their construction. Lastly, they can be naked or insulated. Although they serve a function similar to that of wires or cables, there are many differences that make them preferable in some situations. Busbars are capable of carrying up to 15% more power even with the same cross section as the cable ("Aptiv", 2021). This advantage can be expressed with simple heat transfer equations as follows,

Heat generated by the busbar:

$$q_{\text{gen}} = I^2 \frac{\rho}{A_{\text{cs}}} \tag{2.1}$$

Heat that must escape by natural convection:

$$q_{\text{cool}} = h \, A_{\text{surface}} \, \Delta T_{\text{max}} \tag{2.2}$$

Setting $q_{\text{gen}} = q_{\text{cool}}$ and solving for I gives

$$I_{\text{max}} = \sqrt{\frac{h \, A_{\text{surface}} \, \Delta T_{\text{max}} \, A_{\text{cs}}}{\rho}} \tag{2.3}$$

Hence the continuous current rating follows

$$I_{\text{max}} \propto \sqrt{A_{\text{surface}}} \tag{2.4}$$

where

$I_{\mathbf{max}}$ continuous current rating [A]
ρ resistivity of the conductor [Ohm . m]
$A_{\mathbf{cs}}$ cross-sectional area of the bar [m^2]
h convective heat-transfer coefficient [W . m^{-2} . K^{-1}]
$A_{\mathbf{surface}}$ surface area in contact with the coolant per unit length [m^2]
$\Delta T_{\mathbf{max}}$ permissible temperature rise [K]

While using the same cross-sectional area, busbars can be shaped in different ways to increase surface area. A larger surface area lets heat escape more efficiently. This extra thermal headroom allows the busbar to stay below its temperature limit at a higher continuous current. This makes it possible to carry more current, thus more power, than a wire without overheating, which is beneficial for compact packaging. There are more merits to busbar, such as having a rigid geometry is better for durability, easy maintainability and cost effectiveness. Although the expressions above are for cooling by natural convection, the same square-root relationship holds when heat is removed mainly by conduction.

Heat that must escape by conduction:

$$q_{\mathrm{cool}} = \frac{k\, A_{\mathrm{surface}}\, \Delta T_{\mathrm{max}}}{d} \tag{2.5}$$

where,
k thermal conductivity of the material [W/(m . K)]
d thickness of the material [m]

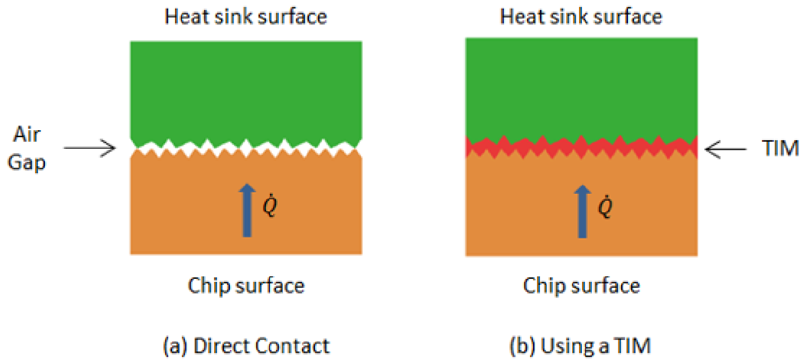
In real life scenario, when a busbar is mounted inside a sealed enclosure, for instance a junction box with little or no airflow, it can still be kept within its temperature limits by conductive paths to active cooling systems. These measures reduce heat and prevent the bar from overheating. In addition, busbars are not the only components that generate heat in a high-voltage environment.

Devices such as fuses and contactors may experience even greater temperature rises under load. Therefore, effective thermal management becomes essential to maintain system reliability and safety. Thermal management strategies for such systems are typically categorised into passive and active cooling methods.

Passive cooling works on the principle of natural heat transfer, i.e. the thermal energy of the source dissipates heat in the environment based on natural convection, conduction, and radiation, where air is usually a medium of dissipating heat. Active cooling consists of an extra mechanical or electrical aid that forces the heat dissipation to take place at a faster pace. This is usually done by conductive paths to a cooling system comprising fans, liquid cooling plates, or thermoelectric devices.

2.1.2 Thermal Interface Material (TIM)

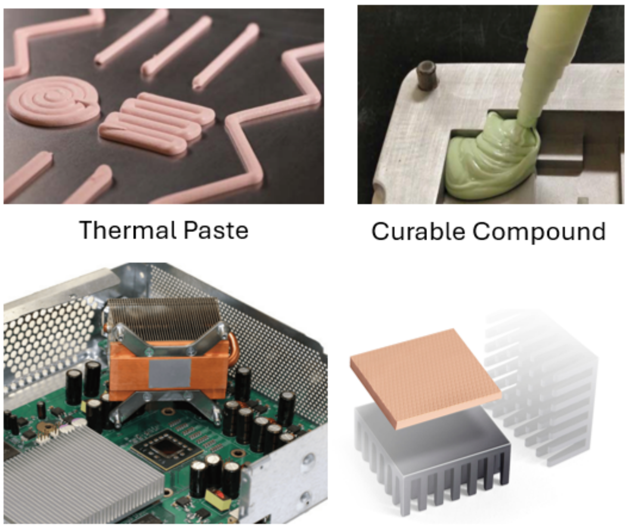
The materials used to improve the thermal coupling between a heat-producing and a heat-dissipating component are called thermal interface material or TIM. Improving the heat transfer between these parts greatly improves the cooling efficiency as well. These materials fill microscopic air gaps that exist between surfaces due to natural roughness or manufacturing tolerances. Since air is a poor conductor of heat, replacing it with a thermally conductive material significantly enhances overall cooling performance. As illustrated in Figure 2.3 (kraFAB, n.d), "chip surface" indicates the heat producing component that transfers the heat to the heat sink. TIM fills the air gap, enhancing overall heat transfer in this example, leading to better cooling.



(a) Direct Contact (b) Using a TIM

Figure 2.2: Difference between direct contact and TIM contact

This material is available in several forms depending on the application, including thermal pastes, curable compounds, phase change materials, and dielectric pads as shown in the Figure **??**. The focus of this project will be on dielectric pads. These pads are soft and possess a polymeric nature similar to that of rubber. As a result, they are susceptible to creep when subjected to a constant load over an extended period. This deformation can compromise any fixation or fastening mechanism that relies on the reaction forces of the material, such as preload in a screw, which may gradually loosen and lead to failure of the intended fixation strategy.



Thermal Paste Curable Compound

Phase Change Materials Dielectric Pads

Figure 2.3: Various types of thermal interface materials

Despite this mechanical limitation, dielectric pads offer favourable thermal conductivity while maintaining excellent electrical insulation. This makes them particularly well suited for high voltage applications. Overall, they provide a balanced solution for both thermal and electrical requirements for the project. However, their long term mechanical stability must be carefully considered during the design phase to ensure reliable and consistent performance over time.

2.2 High Voltage Electrical Behaviour

High-voltage applications behave differently from normal low-voltage circuits. Key concepts are introduced, necessary to understand the technical context and phenomena that needs to be managed.

2.2.1 Electrical Insulation

Insulation is a critical aspect, especially in the case of high-voltage applications, for the safety and reliability of the system. It involves resisting the flow of electrical current between conductive materials at specific places in order to avoid any risk of short circuit or any potential health hazard to a human. Basic terminology for electrical insulation theory which is relevant to this thesis project will be discussed below in further subsections.

Designing for electrical insulation revolves around using materials' inability to transmit/transfer electricity, either by creep on the surface, or penetration through the material, called ”leakage”. This characteristic is mainly dependent on the material's dielectric strength and CTI, rendering the insulation design configuration to use the materials' electromechanical properties in combination with these parameters to fulfil the purpose of the component or product task.

2.2.2 Electrical Breakdown

This section will mainly comprise of electrical theory, however, given the working environment of the fastener in the *TVPDC*, this chapter will also include material breakdown based on the thermal loads from the environment.

Similar to when a material mechanically deforms when subjected to a load surpassing its yield strength, an insulating material can become a conductor (and current flows through it) when subjected to a voltage that exceeds its dielectric strength. This process is called electrical breakdown, or dielectric breakdown, the voltage required is called breakdown voltage. These terminologies can be further discussed below.

2.2.2.1 Dielectric Strength

Dielectric strength can be explained as the maximum amount of electric field a material can withstand without being conductive. This is an intrinsic material characteristic and depends on the composition of the material. Analogous to mechanical yield strength, dielectric strength can be expressed as the ability to resist electrical stress before it fails as an insulator. This strength is usually measured based on the thickness of the material and has the unit of volts per meter [V/m].

2.2.2.2 Breakdown voltage

This can be explained as the maximum voltage applied across the material above which the insulating material stops resisting the electrical flow and becomes a conductor. In mechanical analogy, this can be explained as the maximum load a material can withstand before it fails. The unit for this is volts [V].

The two terms mentioned above are closely related to each other and dictate the properties of insulation of the material prominently. This relation is quite akin to the mechanical relation between strength and loads and how they vary based on the area. It is similarly expressed as follows for dielectric strength and breakdown voltage:

$$Breakdown\ Voltage = Dielectric\ Strength * Thickness \tag{2.6}$$

2.2.3 Dielectric strength parameters

There are several factors that affect the dielectric strength of the material as stated in (Pearmain & Haddad, 2003). As observed from Equation 2.6 thickness affects the dielectric strength as it is inversely proportional to it. Furthermore, the rate at which voltage increases or the duration for which voltage stress is applied directly influences the dielectric strength over time. Even rising temperatures cause a decrease in the strength. These factors are illustrated in (Pearmain & Haddad, 2003) and shown in Figure 2.4

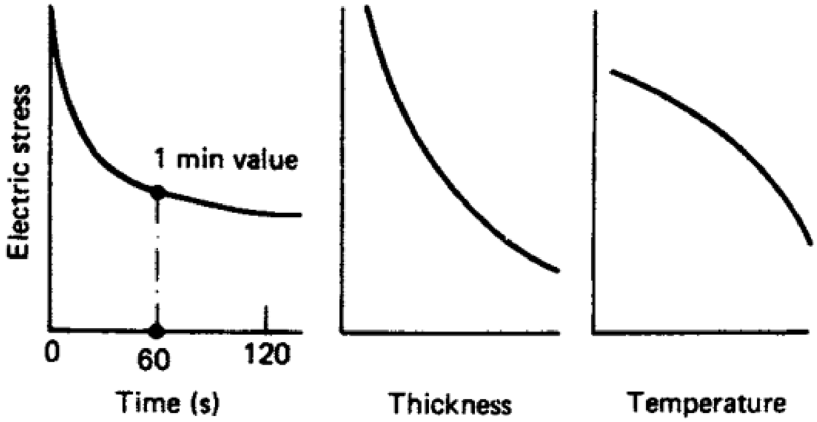


Figure 2.4: Effect of time, thickness and thickness on electric strength. Adapted from (Pearmain & Haddad, 2003).

2.2.4 Electromechanical Breakdown

The environment where the solution is designed to operate offers loads from electrical, mechanical and thermal factors simultaneously - therefore it is useful to understand how the forces affect the strength of the material. In the electromechanical case, materials can deform without collapsing if the electrostatic compression exceeds the mechanical compressive strength, ”The compression forces arise from the electrostatic attraction between surface charges which appear when the voltage is applied. ” (Kuffel et al., 2000, chapter 6.1.3, p 373). From (Stark & Garton, 1955) in unison with (Kuffel et al., 2000), the electromechanical strength revolves around an equilibrium between the electrical compression and the mechanical compressive strength. This is explained by the following formula and explanation taken from (Kuffel et al., 2000) and (eeeguide.com, n.d.).

$$\epsilon_0\epsilon_r\frac{V^2}{2d^2} = Yln(\frac{d_0}{d}) \tag{2.7}$$

or

$$V^2 = d^2\frac{2Y}{\epsilon_0\epsilon_r}ln(\frac{d_0}{d}) \tag{2.8}$$

where
Y = Young’s modulus [Pa]
ϵ_0 = permittivity of the free space [-]
ϵ_r = relative permittivity of the dielectric (material) [-]
d = distance [m]
V = applied voltage [V]
d_0 = initial thickness of specimen material [m]

This thesis is delimited in time and therefore, formulas 2.7 and 2.8 are used for support when investigating characteristics of materials of interest. This can be taken as a reference for future investigations on the topic.

2.2.5 Electrothermal Breakdown

When electric current flows through a material, it heats up the material increasing the temperature. Hence some power is lost in terms of heat. This heat by DC and AC can be expressed as follows according to (eeeguide.com, n.d.):

$$W_{d.c.} = E^2\sigma \tag{2.9}$$

$$W_{a.c.} = \frac{E^2 f \varepsilon_r tan\delta}{1.8 * 10^{12}}\sigma \tag{2.10}$$

where
$W_{d.c.}$ = Heat generated due to DC $[W/cm^3]$
$W_{d.c.}$ = Heat generated due to AC $[W/cm^3]$
E = RMS value for electric field $[V/m]$
σ = Electrical conductivity of the material $[S/m]$
f = Frequency $[Hz]$
ε_r = Relative permittivity of the dielectric material [-]
δ = loss angle of the dielectric material $[^\circ]$

Now alongside referring to (Kuffel et al., 2000), the heat dissipated can be formulated as below:

$$W_T = C_V \frac{dT}{dt} + div(K\ grad\ T) \tag{2.11}$$

where
W_T = Heat dissipated $[W/cm^3]$
C_V = Specific heat of the material $[J/kg.K]$
T = Temperature of the material $[K]$
K = Thermal conductivity of the material $[W/m.K]$
t = Time taken to dissipate heat $[s]$
ε_r = Relative permittivity of the dielectric material $[-]$
δ = loss angle of the dielectric material $[^\circ]$

Now, when the heat dissipated is equal to the heat generated plus the heat radiated, equilibrium is reached. If the heat generated exceeds the heat that gets dissipated, then the material experiences thermal instability and hence electrothermal breakdown. This can be explained through an illustration from (Kuffel et al., 2000), where a material is subjected to three different electric fields.

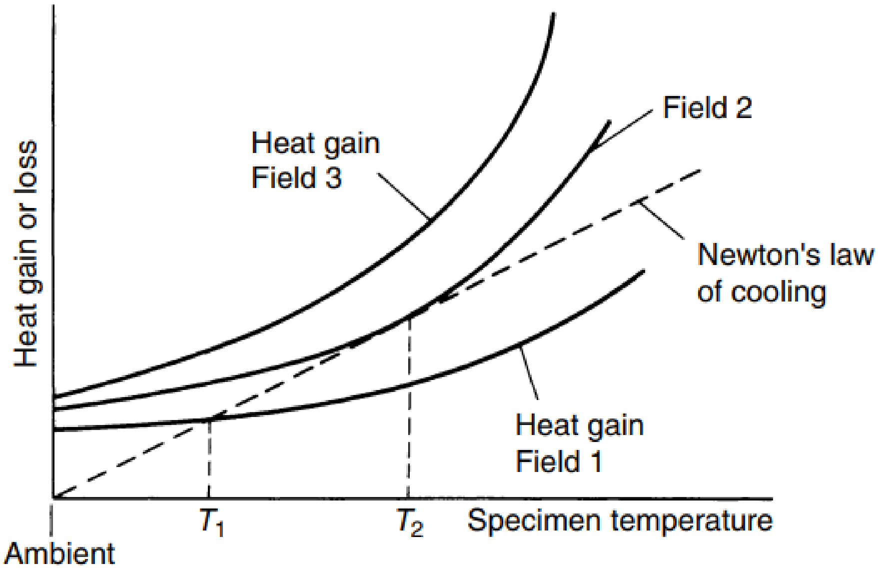


Figure 2.5: Thermal instability in solid dieletric materials

As explained in the journal, Field 1 achieves thermal stability or equilibrium at T_1, while Field 2 is thermally unstable at T_2 and Field 3 never achieves equilibrium as the heat generated is always more heat dissipated causing a breakdown.

The above models for electromechanical and electrothermal breakdown can be studied separately, but according to the paper (Zebouchi & Malec, 1998), they can be combined to better understand the behaviour of the material. This is used to get a better insight in what material characteristics and parameters might be used to search for advantageous materials for this project.

2.2.6 Electrical Discharge

Electrical discharge, arcing, or "clearance" are re-occurring terminology throughout this project. They refer to the phenomena of electrical "unloading" in the form of a spark, lightning, or arc that travels between one electrode and another. In an electrical circuit, this can cause short circuiting, which can have critical consequences.

In this project, *Paschen's law* is used as a tool to estimate and evaluate the distance of the potential electrical discharge. "Paschen's law is an equation that gives the breakdown voltage, that is, the voltage necessary to start a discharge or electric arc, between two electrodes in a gas as a function of pressure and gap length" (Wikipedia, 2025). *Paschen's law* follows:

$$V_B = \frac{Bpd}{ln(Apd) - ln[ln(1 + \frac{1}{\gamma_{se}})]} \tag{2.12}$$

Where
A = Saturation ionization at a particular electric field/pressure [constant]
B = Constant related to excitation and ionization energies [constant]
γ_{se} = Secondary-electron-emission coefficient

p = gas pressure [Pa]
d = electrode gap distance [m]

Experimental values for A and B in air were measured at values 15 and 365 respectively (Martins & Pinheiro, 2011), the constants represent the saturation ionisation in the gas at a particular electric field / pressure (A), and excitation and ionisation energies (B) (Wikipedia, 2025). The value of γ is 0.01 (Martins & Pinheiro, 2011, p.116). For detailed analysis, further research is necessary. To understand the topic and expand the technical depth, humidity and cleanliness could be researched and used as variables for a more detailed analysis or modelling of a particular condition in a production plant or maintenance facility.

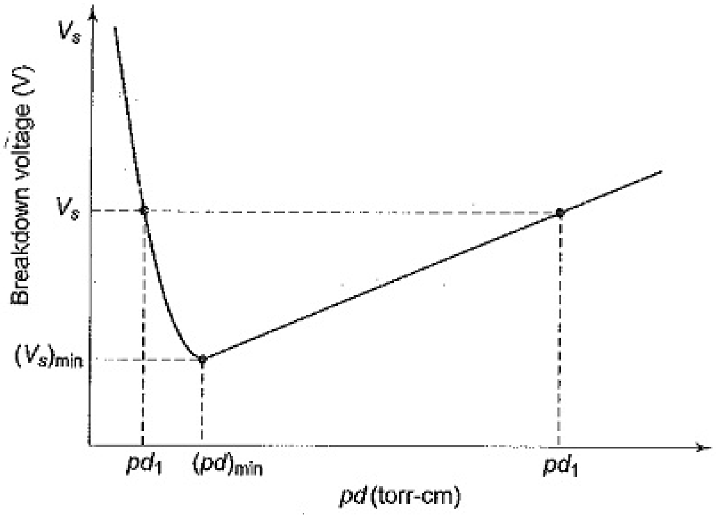
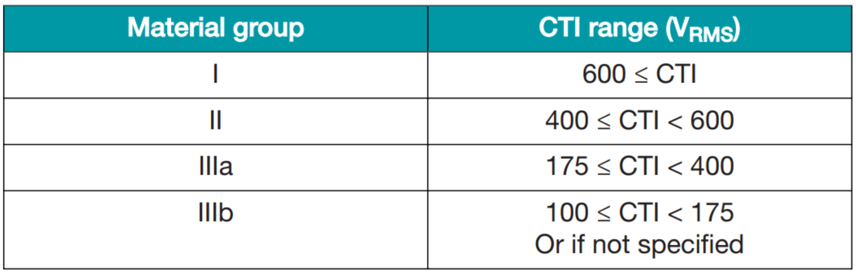


Figure 2.6: Paschen's breakdown voltage curve. Credit (eeeguide.com, n.d).

Summarised and simplified, Paschen's law is useful to understand what parameters affect the electric arc (breakdown voltage) between electrodes. As stated in (eeeguide.com, n.d), the breakdown voltage in a gas (in this project: air) is proportional to the product of the gas pressure and the distance between the electrodes. It is known that pressure can vary depending on elevation and atmospheric pressure; if this is considered with a feasible value range, the remaining variable is the distance between the electrodes. This will be used in the project calculations and considerations as it is useful to obtain an indication of the expected behaviour of potential electric arcs in this high-voltage application.

2.2.7 Tracking and Comparative Tracking Index

Tracking is electrical leakage along the surface of a material where the material carbonises between the electrodes and leaves a "track" (Pearmain & Haddad, 2003, chapter 7.2.3.4), for reference, see Figure 2.8. *International Electrotechnical Commission* defines it as "... tracking - progressive formation of conducting paths, which are produced on the surface and/or within a solid insulating material, due to the combined effects of electric stress and electrolytic contamination." (IEC, 2020, c. 3.1, p.6).



Material group	CTI range (V_{RMS})
I	600 ≤ CTI
II	400 ≤ CTI < 600
IIIa	175 ≤ CTI < 400
IIIb	100 ≤ CTI < 175 Or if not specified

Figure 2.7: Material groups based on the corresponding CTI value. Table source: (Zhang & LaBella, 2024)

Some electrically non-conducting materials track more than other, to keep *track* of the differences and how different materials rank, there is a comparative tracking index (CTI). (Zhang & LaBella, 2024, p.3, tab. 1) explains that the CTI categorises the insulating materials according to the voltage at which the electrical breakdown occurs. The CTI test is determined by adding 50 droplets of water - ammonium chloride solution and applying a stepwise increasing voltage until 0.5 A of current is flowing through the material. The highest voltage the material could withstand before conducting the current becomes its CTI rating according to IEC 60112 (Zhang & LaBella, 2024) (IEC, 2020).

Figure 2.8: Visualization of tracking in the form of a Lichtenberg figure on a panel of wood. Image credit: (Helebrant, n.d.)

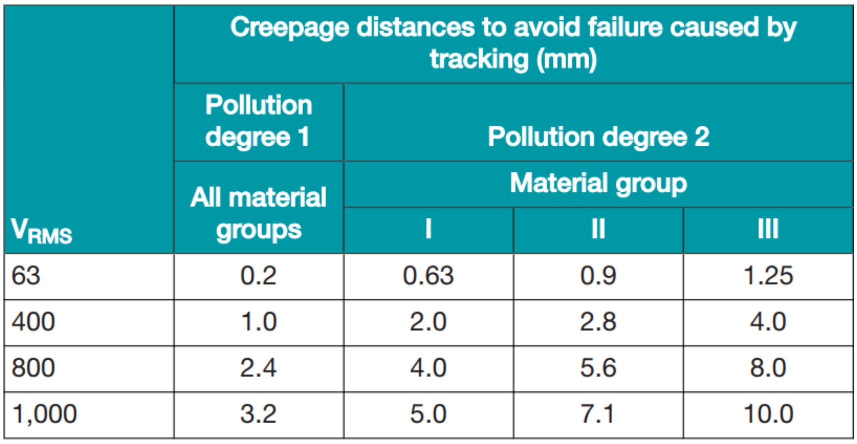
Tracking can also occur in gases; however, the term is more accurately called "clearance" in this project and is described in further detail in Section 2.2.8.

2.2.8 Creepage and Clearance

Creepage and clearance discharges are electrical phenomena that can occur in electrical applications (mainly high-voltage), where the voltage breaks down and arcs via the air or along a material. Originally derived from *Paschen's law*, the breakdown voltage is proportional to the product of atmospheric pressure and the distance between the electrodes. Standards for distancing electrodes such as (International-Electrotechnical-Comission, 2020) uses a testing altitude set at <=2000 m above sea level (the equivalent barometric pressure will be that of elevation of 2000 m), according to *Paschen's law* and Figure 2.6, this could mean that for some applications in high elevations, the lower pressure and thereby an electrode distance safety margin must be considered. In addition, creepage and clearance also depend on factors such as pollution, humidity, the type of insulating material, and more parameters.

Figure 2.9: Lightning strike visualizing a natural occurrence of the clearance phenomena. Credit: (Piironen, 2021).

Clearance, or rather, electrical discharges occur naturally and are simplest visualised through a lightning strike. In the following image, the clouds and ground can be seen as two electrodes, where the clouds have a surplus of electrical charge, and the ground is neutral. At a certain charge (frictional charge in the clouds), the voltage exceeds the breakdown voltage for the gaseous medium (air) and the distance to the ground according to *Paschen's law* which, in turn, triggers the electrical discharge, i.e. lightning strike.



V_{RMS}	Creepage distances to avoid failure caused by tracking (mm)			
	Pollution degree 1	Pollution degree 2		
	All material groups	Material group		
		I	II	III
63	0.2	0.63	0.9	1.25
400	1.0	2.0	2.8	4.0
800	2.4	4.0	5.6	8.0
1,000	3.2	5.0	7.1	10.0

Figure 2.10: IEC 60664 recommended creepage distance based on pollution. Table source: (Zhang & LaBella, 2024).

In almost every environment, pollution particles occur, the risk of a particle connecting two electrodes, thereby acting as a conductor, increases with the size and the number of the particles. In Figure 2.10, the pollution degree is a classification on how big and how many particles can be expected in the gas where the electrodes are located, along with the tracking characteristics of the material used, a minimum safety distance of creepage value can be obtained. This project assumes the worst-case scenario for these values and uses 10.0 mm as minimum creepage distance.

Inorganic materials such as ceramics, do not track. They belong to the group *Non-tracking materials* where the creepage distance does not need to be greater than the clearance distance. Furthermore, IEC 60664-1 states ”A creepage distance cannot be less than the associated clearance so that the shortest creepage distance possible is equal to the required clearance...” and that there is no physical relationship between the phenomena other than these limitations of minimal clearance in air and the minimum acceptable creepage distance (along the material) (International-Electrotechnical-Comission, 2020).

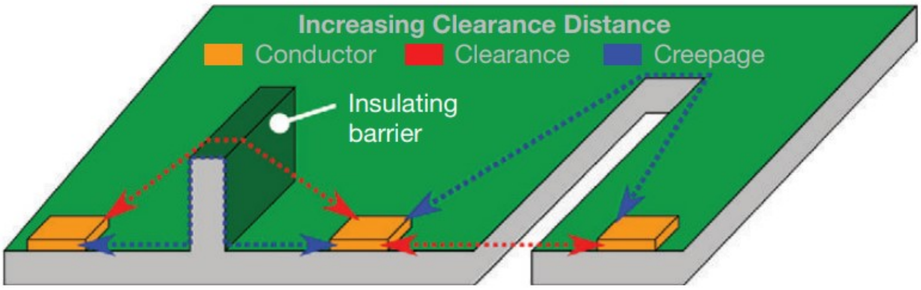


Figure 2.11: Visualization of electrical creepage and clearance between conductors. Retrieved from (“Clearance and Creepage in Circuits Up to 1500 VDC, Considering Cost and Space Requirements for Film Resistors”, 2024)

2.3 Fasteners

The function of a fastener is to mechanically join two or more components together. They play a crucial role in the integrity and safety of various kinds of structures. They can be classified into two categories i.e. Permanent fasteners and Non-permanent fasteners. There are various types of fasteners within these two categories, where the authors considered them in the concept generation process and will briefly discuss about them. However, to keep the theory relevant given the project resources and the result of the *Pugh matrix* in Section 4.10, this section will dive deeper in the theory of bolted joints. Hence, starting with a brief description of different fastening mechanisms as follows:

Welding comprises a process of joining or fusing two materials with the help of heat. This is a type of permanent joint that provides high strength to the components.

Rivets are a type of permanent fasteners that deform plastically and hold the components in place. It looks similar to a bolt, but it is not threaded.

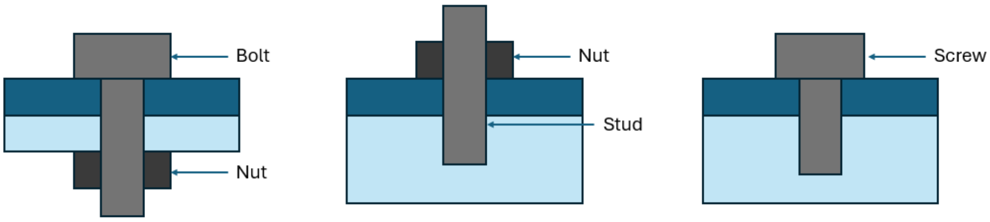
Adhesives are used to chemically bond two or more components which create a permanent bond between them, hence securing them in place.

Press fits, also known as interference fits, are a type of joint where they rely solely on the friction force between the tolerance and are highly dependent on low tolerances.

Compliant mechanisms are a type of non-permanent joints that work on the principle of elastic deformation and stress differences. This includes mechanisms like spring-loaded clamps, snap fits, etc.

2.3.1 Threaded Fastener

A threaded fastener uses parts such as bolts, screws, studs, and nuts to mechanically secure and fasten the components. They can be fastened in three ways, the first being a bolted joint, where two or more components are clamped together using a bolt inserted through the parts and tightened using a nut on the opposite end. Another type would be a stud joint, which is a headless threaded bolt screwed into a tapped housing and secured in place with a nut. Similarly to this, a screw joint is made, where the screw is mated with a tapped component. They are illustrated in Figure 2.12. Another advantage of using threaded fasteners is their excellent maintainability. Compared to other joining methods such as welding or rivets, which are permanent, threaded fasteners allow for easy disassembly. This makes them ideal for applications where regular maintenance, inspections, or replacement of parts is required, such as the automotive sector. This simplifies the process for serviceability, which reduces downtime and is also beneficial for recyclability purposes.



(a) Bolted Joint (b) Stud Joint (c) Screw Joint

Figure 2.12: Cross section of the types of bolted joints

These types of joints provide a clamping force to the parts to hold them in place and support the working conditions without getting loose. Bolts, screws, and studs typically work like a spring in this kind of fastening mechanism. When tightened, the bolts stretch elastically, generating a tensile force. This preload provides a clamping force that holds the joint together. They are similar to springs when they are screwed in or torqued in with the help of a nut. This elongation of the bolt generates a tensile force in the bolt which provides a reaction force to the clamped members in the form of compressive force. The tension in the bolt is crucial because it governs the ability of the joint to resist external loads and maintain the clamping force under dynamic conditions.

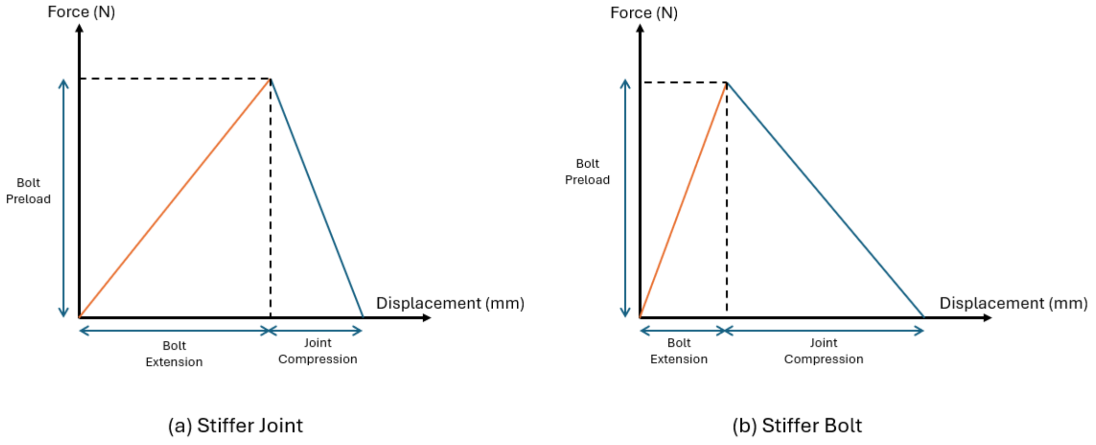
This tensile force in the bolt is also referred to as *Preload* and needs to be controlled to a value that might be optimal for its usage; otherwise, it could lead to failure of the assembly. Given the elastic nature of bolts, if they are preloaded correctly and ideally with more load than it has to sustain, it can help reduce the alternating or fluctuating stresses and improve the fatigue life of the bolt while also ensuring a good clamping force over a period of time, as demonstrated in the article (Rasmussen, 2021).

Generally, the preload should be more than the maximum tensile force the joint will experience. Hence, the selection of the bolt size is an important step, as different bolt sizes and material will have different values for preload. The following equation can be used according to (Mechanicalc, n.d.) which also references the handbook (Budynas & Nisbett, 2015) to find conservative preload values based on the strength of the material:

$$F_{PL} = \begin{cases} 0.6375\sigma_{\text{yield}}A_{\text{yield}} & \text{for non-permanent joints} \\ 0.765\sigma_{\text{yield}}A_{\text{yield}} & \text{for permanent joints} \end{cases} \tag{2.13}$$

where
F_{PL} Preload Force [N]
$\sigma_{\textbf{yield}}$ yield strength [MPa]
$A_{\textbf{yield}}$ cross section area of the bolt [mm^2]

The relative stiffnesses of the bolt and the clamped parts affect the behaviour of the joint. Ideally, the clamped parts should be stiffer than the bolt, so that under external loading conditions the load is absorbed more by the clamped parts (reducing their compression) than by increasing the tension in the bolt, as explained in the article (Ansys Innovation Space, 2022) which also refers to the handbook (Budynas & Nisbett, 2015). Figure 2.13 explains the relation between the force experienced by the bolt and the clamp with respect to its displacement and the slope representing their stiffness.



(a) Stiffer Joint

(b) Stiffer Bolt

Figure 2.13: Joint diagram for stiffer bolt and stiffer joint assembly

The joints can be loaded in different ways: axially, by shear, or through a combination of both. Axial loads are mainly resisted by the tensile strength of the bolt, while shear loads are initially resisted by the frictional force between the clamped components. Once this friction is overcome, the shear strength of the bolt becomes the primary resisting mechanism. The behaviour of the joint under combined loading depends on the mechanical properties of both the bolt and the clamped components.

These conditions generally hold true when the clamped parts are stronger than the bolt. However, if this is not the case, the joint can be susceptible to various failure modes, including shear failure of the components, yielding or fracture of the bolt, bearing failure at the contact interfaces, or even tensile failure of the clamped members. These failure modes will be discussed in more detail in Section 2.4.

In order to achieve the correct preload, there are some relations which provide equations to estimate the torque required to screw into the fastener which helps us achieve the correct preload. According to (Mägi et al., 2017, p.67, eq.2.10), the torque can be derived with the following equation:

$$M_{tight} = F_{clamp}(0.16P + 0.58\mu d_2 + \mu_b r_b) \tag{2.14}$$

where
M_{tight} Assembly Torque [Nm]
F_{clamp} Clamping Force [kN]
P Thread pitch [mm]
μ Thread friction coefficient [-]

d_2 Contact diameter in the threads [mm]
μ_b Friction coefficient between bolt head and clamped part [-]
r_b Contact radius under bolt head [mm]

where d_2 can be expressed as

$$d_2 = d - \frac{3\sqrt{3}}{8}P \tag{2.15}$$

This equation is also further simplified according to (Budynas & Nisbett, 2015) which can be written as:
insert eqn

2.4 Failure modes for typical fasteners

In order to make the solution safer and more reliable, some relevant failure modes must be investigated and analysed. This section presents the used failure modes for a typical bolt and the loading conditions from shock loads the truck might experience (see Section 4.4).

Tensile failure of the bolt: Tensile failure occurs when the bolt is subjected to axial loading or tensile forces which exceeds beyond the tensile strength of the material of the bolt. This causes a fracture or breakage of the bolt in its length. The maximum force which the bolt can sustain without breaking can be expressed as follows:

$$F_{tensile} = \sigma_{tensile} * A_{tensile} \tag{2.16}$$

where
$F_{tensile}$ Maximum Tensile Force [N]
$\sigma_{tensile}$ Tensile Strength [MPa]
$A_{tensile}$ Tensile area of the bolt [mm^2]

Shear failure of the bolt: This failure is similar to the tensile failure, the difference being that the load acts perpendicular to the axis of the bolt. The plane in which the load acts is called the shear plane. The maximum force which the bolt can sustain without shearing can be expressed as follows:

$$F_{shear} = \tau_{shear} * A_{shear} \tag{2.17}$$

where
F_{shear} Maximum Shear Force [N]
τ_{shear} Shear Strength [MPa]
A_{shear} Shear area of the bolt [mm^2]

Bearing failure caused by bolt: Typically occurs in bolted joints where the material surrounding the bolt, or the contact area of the material with the bolt experiences bearing stresses, causing deformation of hole and making the shape more elongated. The maximum load at which the component deforms can be calculated as follows:

$$F_{bearing} = \sigma_{yield} * A_{bearing} \tag{2.18}$$

where

$F_{bearing}$ Maximum Bearing Load [N]

σ_{yield} Yield strength [MPa]

$A_{bearing}$ Bearing area [mm^2]

Thread stripping strength: Another failure mode that could be of particular interest is the stripping strength of the threads. According to (Alexander, 1977), which talks in detail about the analysis and design of threaded assemblies, threads could be damaged either of the bolt or the tapped component depending on the shear strength of the material. The shearing cross-section area for the bolt ($\mathrm{A_{tsB}}$) and the tapped component/nut ($\mathrm{A_{tsN}}$) under axial loading can be derived as follows based on nominal and minimum dimensions of the thread.

$$A_{tsB}(nom) = \pi * D_1 * (\frac{L_{eff}}{P}) * (\frac{P}{2} + (d_2 - D_1) * tan30°) \tag{2.19}$$

$$A_{tsB}(min) = \pi * D_{1,max} * (\frac{L_{eff}}{P}) * (\frac{P}{2} + (d_{2,min} - D_{1,max}) * tan30°) \tag{2.20}$$

$$A_{tsN}(nom) = \pi * d * (\frac{L_{eff}}{P}) * (\frac{P}{2} + (d - D_2) * tan30°) \tag{2.21}$$

$$A_{tsN}(min) = \pi * d_{min} * (\frac{L_{eff}}{P}) * (\frac{P}{2} + (d_{min} - D_{2,max}) * tan30°) \tag{2.22}$$

where

L_{eff} Effective thread engagement length [mm]

D_1 Nut thread inner diameter [mm]

P Thread pitch [mm]

d_2 Bolt thread pitch diameter [mm]

$d_{2,min}$ Minimum bolt thread pitch diameter [mm]

$D_{1,max}$ Maximum nut thread inner diameter [mm]

d Nominal thread diameter [mm]

D_2 Nut thread pitch diameter [mm]

d_{min} Minimum bolt thread outer diameter [mm]

$D_{2,max}$ Maximum nut thread pitch diameter [mm]

Using the shearing principle in equation 2.17, the authors used the cross-sectional shearing area found above and the respective shearing strength of the materials to find the maximum force it can handle. Figure 2.14 shows how the joint might fail depending on the relative shear strength of the bolt or nut.

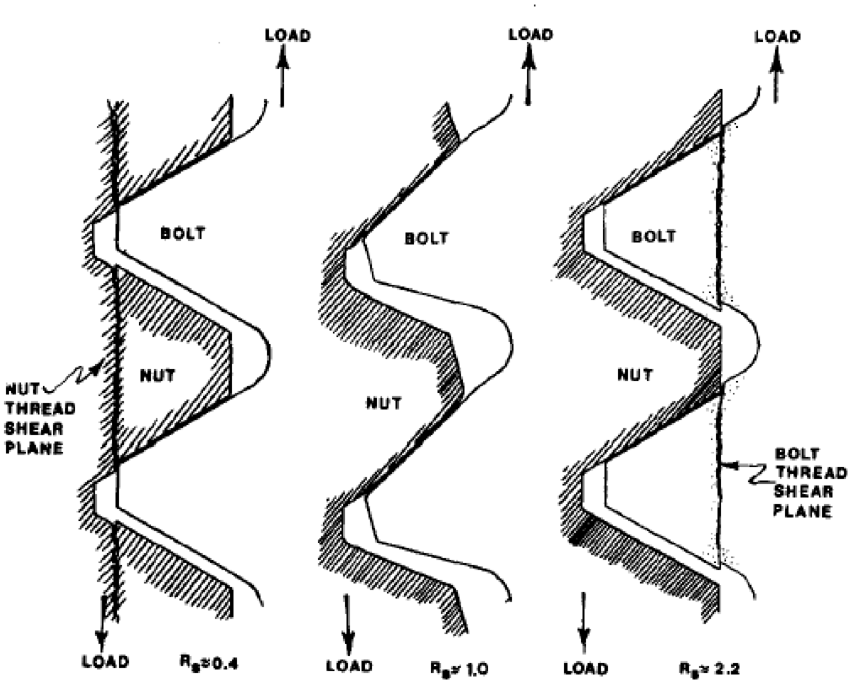


Figure 2.14: Illustration of shearing or stripping of the threads of the bolt and nut (Alexander, 1977)

Tearout Failure: Typically observed in inserts fixed to a panel or plate-shaped structure. When the insert is loaded axially and fails due to shearing or tensile failure of the material with lesser strength. It follows the same principle as equations 2.16 and 2.17.

3

Methods

The methodology provides information on how the investigation was conducted, chronologically what product development methods were used, and the authors' views on how the different steps of the process were important to the project. The explorative, generative, and selective phase of the project will follow the five-step method presented in Ulrich et al., 2011a and below:

1. Clarify the problem - Understanding and decomposing the problem, focus on critical sub-problems.
2. Search Externally - Patents, experts, literature, benchmarking.
3. Search Internally - Individuals, experts, group.
4. Explore Systematically - Classification tree, combination table.
5. Reflect on the solutions and the process - Constructive feedback. Then iterate.

Figure 3.1 provides a compressed and general overview of the project workflow. In the overview, "Problem Decomposition" concludes the initial process of understanding and breaking down the problem into smaller sub-problems. In the project, this will be done again, officially, after the interviews and collecting more information externally.

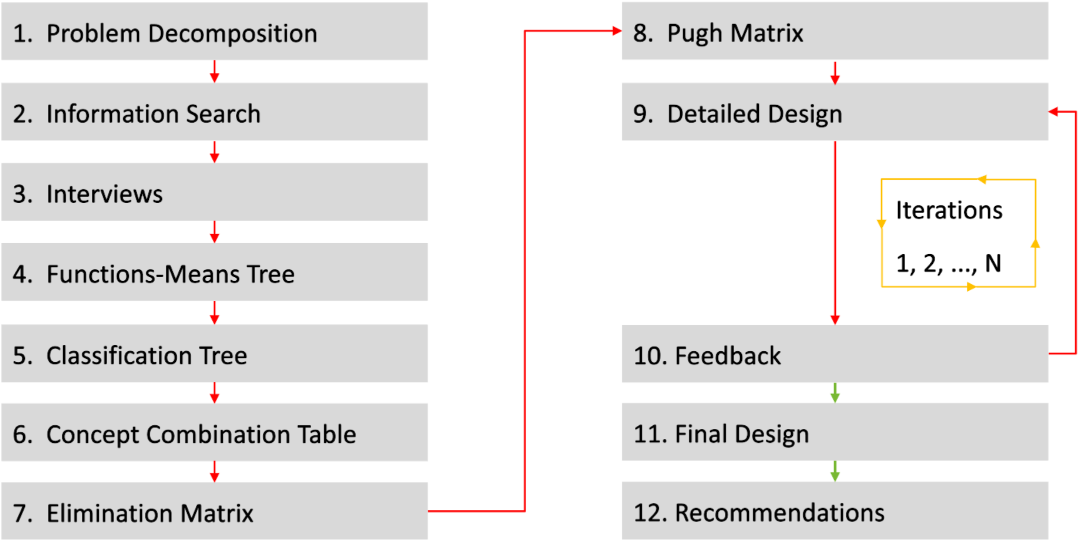


Figure 3.1: Methodology overview

The purpose of the methodology is to quickly gain knowledge of the solution that provides the highest value to the problem, iterate, and adjust it to the test results.

In the end, this aims to deliver one or more concept suggestions or a potential new solution evaluated and investigated. The solution should not need to alter the wiring schedule/configuration nor the cross section of the busbars nor other components inside the TVPDC. However, if a complementary solution can improve the overall result, this can be suggested as a separate action for improvement in combination with the new concept(s) suggested. The solution aims to be used in different busbar components, not only inside TVPDC.

This entices the thesis to initially analyse, understand, and interpret the constraints and requirements the current solution faces in the TVPDC box so that a systematic approach to product development can be applied to the problem. Following, developing, analysing, and evaluating new fixation solution/method and potentially prototypes for the busbars inside the TVPDC box with respect to adherence to the requirements.

3.1 Initial Knowledge Search

The initial search comprises the introductory information gathering process that will form the basis for how to understand and tackle the problem in the subsequent steps of the process. This was achieved through start-up meetings with manager and supervisor respectively as well as introduction to the colleagues at the working site while asking about their quick take on the function of the product.

3.2 Interviews

Given scarce availability of external literature and information sources on the subject, the authors decided to take a qualitative approach for the interviews focusing on internal knowledge within the company, arguing that Volvo is the ”customer” of the project. The goal of the interviews was to obtain knowledge about the problem and understanding the entirety of the components and the system to allow optimal conditions for a successful investigation and, thereafter, product development. The purpose of the interviews and obtaining the knowledge therefrom was to understand and interpret which direction the project had to be steered towards to optimise the chances of a valuable product development outcome.

Ten semi-structured, open interviews were conducted face-to-face with 12 people within the company. Furthermore, the audio from the interviews was recorded and transcribed into separate documents, this would help identifying the customer needs. The interviews comprised Mechanical Design Engineers, Maintainability Engineers, Technical Preparation Engineers, Lead Engineers and some pioneers of the current solution who worked across different disciplines or components. The questions were tailored according to the specialization of the engineer and retrofitted during the interview. This aided in getting an overall insight to the problem through all perspectives of different engineers rather than a few aspects. Gaining this knowledge would help in aiming to develop a product which might be good in almost all scenarios.

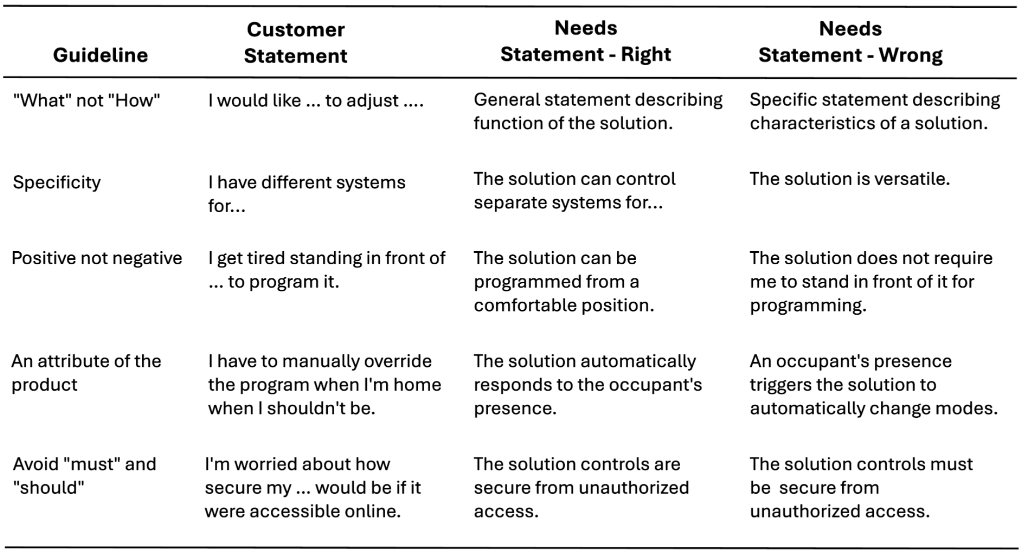
The interviews were started with an introduction to the thesis topic. Owing to the experience they held, the interviewees were suggested to share all the knowledge that might be relevant to us even if not explicitly asked. This would make the authors aware about things that could have been missed from asking to the next interviewees. Even if that information would not be crucial, it will add up to the knowledge pool. The interview then proceeded with simple questions to understand the interviewee better and thereby allow for adapting the interview based on their knowledge to the topic. This implied asking questions like "*Please explain your main areas of responsibility*" to later tie their current, and most recent knowledge to their relation to busbar fixation and more. This way, the interviews provided a nuanced, holistic view to how and why the busbar fixation interacts with different components in and around the TVPDC as many of the workers had changed area of responsibility since the development of the current solution.

For each interviewee, separate questions were prepared with regards to their known expertise. The specific questions were divided into mechanical design (including busbar, TIM, casting, fastener), assembly and after market sections. The majority of the questions pertaining to mechanical design were focused on the design of the solution, components affected by the solution, tolerances, material selection and early concept development and revisions. The issues related to each component were also discussed in detail. In addition, the procedure for assembly and after market were also taken into account.

Questions were asked on the assembly sequence and its efficiency with the current solution, and also included principles of DFA. This helped the authors understand how the solution's design impacts the assembly process, which mostly involved calculating tolerance stack-up because of the increased number of pieces. Lastly, maintenance and repair aspects of the TVPDC addressed the suggestion of considering serviceability since the initial phase of development. It was understood that using fewer and easy-to-repair parts, or standard parts would make after-market context and service-ability more efficient. Ultimately, not having to repair anything would be optimal.

3.3 Needs Identification

The interviews were analysed and documented, wherefrom a list of customer statements were compiled. The list was documented in a customer statement-to-needs statement table (maybe add table if we can since it's very general and no classified data, refer to that table under results in that case). Interpreting the raw data in terms of customer needs was extracted from (Ulrich et al., 2011b, Exhibit 5-7, Page 87), see Figure 3.2. The list is located in Table 4.1. The interviews are conducted with engineers working on or around the fixation system, rendering precise answers and thereby less room for interpretation.



Guideline	Customer Statement	Needs Statement - Right	Needs Statement - Wrong
"What" not "How"	I would like ... to adjust	General statement describing function of the solution.	Specific statement describing characteristics of a solution.
Specificity	I have different systems for...	The solution can control separate systems for...	The solution is versatile.
Positive not negative	I get tired standing in front of ... to program it.	The solution can be programmed from a comfortable position.	The solution does not require me to stand in front of it for programming.
An attribute of the product	I have to manually override the program when I'm home when I shouldn't be.	The solution automatically responds to the occupant's presence.	An occupant's presence triggers the solution to automatically change modes.
Avoid "must" and "should"	I'm worried about how secure my ... would be if it were accessible online.	The solution controls are secure from unauthorized access.	The solution controls must be secure from unauthorized access.

Figure 3.2: Adaptation illustrating guidelines for writing needs statements from *Product Design and Development* (Ulrich et al., 2011a, Exhibit 5-7).

The list is a superset of all customer needs extracted from the interviews. Realising all needs might not be feasible. In addition, the technical and economic feasibility needs are integrated with the list and compiled into the product specifications.

3.3.1 Priorities of Needs

Further, the needs were arranged into a hierarchy based on the process from (Ulrich et al., 2011a, Chapter 5-6, page 87-109) and on the interviews along with the perceived needs extracted from off-interview conversations with experts and design engineers internally. The needs were grouped and then ranked by occurrence. Subsequently, they were given an importance based on the vitality of solving the functions of the fixation system regarding the core values stated in Section 1.1 which are a reduction of the *Volvo* core values, found at (Volvo, 2025, Values and Whistleblowing).

For the purpose of developing a practical solution given the scale of production, cost was also considered an important characteristic. The needs and their importance scores were reviewed together with the *Volvo* supervisor to synchronise reasoning with respect to the *Volvo* ”perspective” on the matter. This was perceived as important by the project team given that the customers, i.e. the engineering team at *Volvo*, have a latent need of keeping up with the brand of the company and thereby its values even though they might not mention it during the interviews given that it might be pre-understood for them.

3.4 Problem- and Function Decomposition

The problem proved uncertain, as, initially, some areas were challenging to find knowledge about. For this reason, the authors decided to delay the breakdown of the problem until more of the complexity and the extent of the problem were known. From the documentation of the interviews, the spoken and identified problems were analysed from descriptions, potential underlying meaning, and frequency of occurrence by the interviewees.

In parallel, the unspoken problems were analysed and mapped to the authors' own understanding in a separate document. These data sets could directly be used as a base in the breakdown or decomposition of the problem, but also for the investigation of the function of what the system of busbar fixation provides and what is the intended function of the system. Figure 3.3 shows the breakdown of the problem after compiling knowledge from 12 interviewees. In addition, the unspoken problems could be further researched and used to find answers to areas that had not been addressed before. The risk is that engineers did not mention all the problems or challenges because of perceived complexity or bias to what this project was about, thus keeping information.

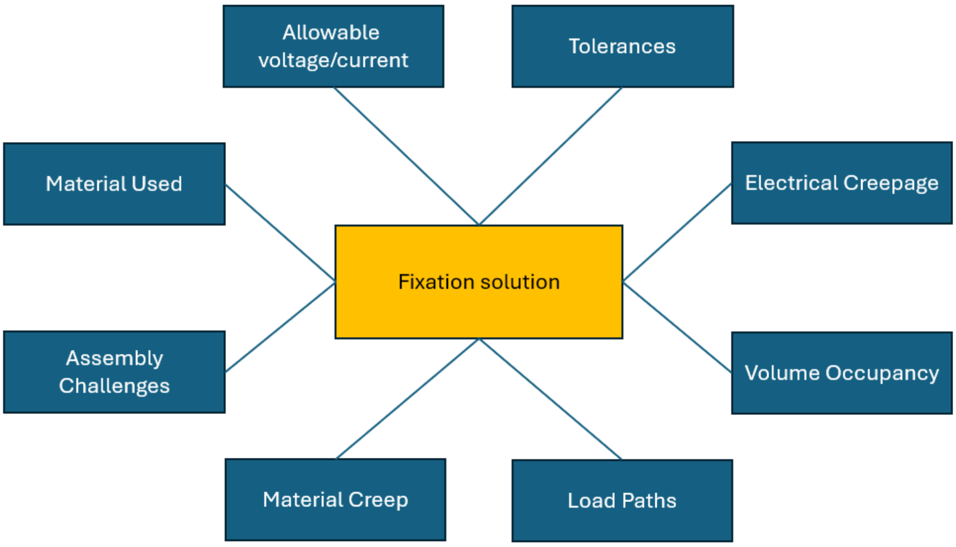


Figure 3.3: The initial interpretation of how the task could be decomposed into areas of improvement.

In addition, the breakdown of the problem was analysed and comprised the basis for the function decomposition. In turn, the function decomposition acts as a premature iteration of the subsequent step in the development process: the function-means tree. Different parts of the subsystems have different and unique functions that together form the characteristics of the solution. The ”function decomposition tree” breaks down the function into simpler subfunctions and is visualised in Figure 3.4.

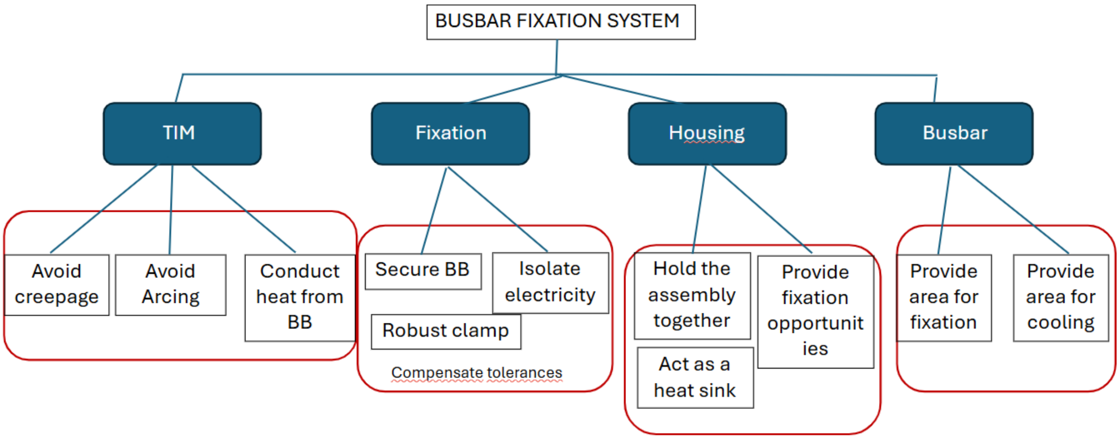


Figure 3.4: Early iteration for function decomposition, later used for constructing *Function-Means Tree*. "BB" meaning busbar.

3.5 Function-Means Tree

When developing a product, it is crucial to have a clear understanding of its purpose and the various functions it needs to perform. The *Function-Means Tree* is a method used in product development to identify these primary functions and determine how they can be achieved through specific means or methods.

This systematic approach helps break down the problem in a structured way, making it easier to pinpoint each function and think of superior ways to solve it. It provides a clear perspective on how each solution or "means" can enhance the product's performance and ensure that it meets its objectives.

The hierarchical structure of the *Function-Means Tree* allowed the authors to start with the broad primary functions at the top level and then break them down further into more specific tasks. From there, the possible solutions for each function could be identified, these are known as the "means". This process also encourages the exploration of multiple alternatives, allowing the project to select the least inferior one.

By using this method, all aspects of the functionality of the product are considered, while potential gaps or weaknesses are discovered in parallel. Ultimately, the *Function-Means Tree* strengthens the understanding of how the product will be used and ensures that every angle in its design is covered.

Additionally, these functions may be interdependent and interconnected, and they can be further broken down into sub-functions, which will be explored in the following subsection.

3.5.1 Enhanced Function-Means Tree

The enhanced function-means tree takes the method one step further, allowing a more detailed breakdown of the relations and interdependences of the functions and means; see Appendix B.1. (Müller et al., 2019) explains the *Enhanced Function-Means Tree* (EF-M) as a model for ”representing the design space and integrating novel solutions into the existing product structure...”.

The article continues with stating that the model is meant to complement the F-M tree by allowing the opportunity to representing constraints of the designs along with interdependencies between functions and means in different ”branches” of the tree. (Mokhtarian et al., 2016) also suggest function modelling as a support for design exploration, also explaining that the model supports two kinds of categories; developing a radically new solution, or an improvement of an existing one, which makes the EF-M tree effective for set-based concurrent engineering projects, i.e., this project.

The end goal for both articles is to support innovative ideation, a key feature to achieve research question 2 of this project. The authors reason that, for the sake of the thesis and using comprehensive visualisation for more complex problems in the future, applying the EF-M tree can improve the concept generation outcome by widening and exploring more of the design space. The EF-M tree enables this by communicating interdependencies through statements as; *is constrained by* (icb), *is solved by* (isb), *requires function* (rf), *is partially met by* (ipmb), and *interacts with* (iw). The mentioned elements allow for effective communication and, in extension, understanding of the system or product under development.

In this project, the EF-M tree will be used mainly to visualise and organise how the sub-functions and means interact with each other and the constraints given the problems and functions have already been decomposed in previous sections. The final outcome of the EF-M tree will provide a broad design space and hinder non-reasoned narrowing of the solutions. In addition, the sub-functions will be forwarded to the *Morphological matrix*, subsequent step of the product development process according to (Ulrich et al., 2011a).

3.6 Concept Classification Tree

The classification tree uses the functions defined from the *Function-Means Tree* to search and classify means that fulfil or solve the function.
It is a useful tool that complements the functions defined in the *Function-Means Tree*, or *Enhanced Function-Means Tree* by solving the decomposed problems separately and thereby solving the sub-problems individually for what the function is stating. This simplifies the problem solving process for the team as the individual sub-solutions will continue to cross-combination in the *Morphological matrix* in a later stage where all sub-solutions are tested and combined for their feasibility.

The classification tree is useful for the project to visualise and separate the different functions in order to come up with more and more creative means before starting the concept generation. This is shown in Figure 4.3 where some fixations were found from the inspiration of the ”class”, or type of sub-solution which brought new ideas to solve the sub-problem.

3.7 Benchmarking

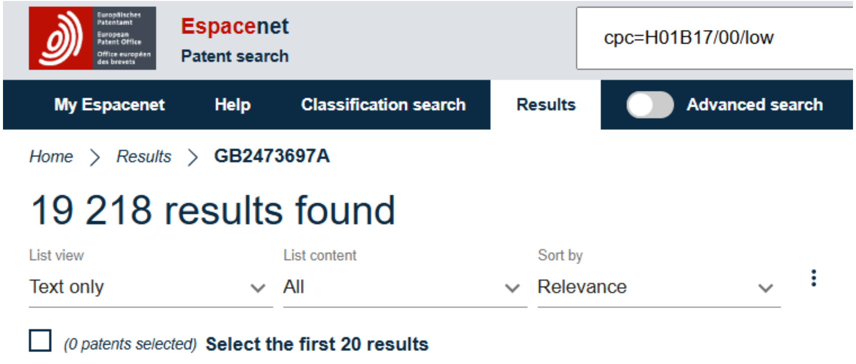
In addition to the knowledge pool and insights that were gained by interviewing people on this topic, benchmarking of competitor products and other electric vehicles with relevant architecture were also carried out. This step was quite helpful, as collecting this kind of data would aid in decision making for a final concept.

With the help of "A2MAC1", 2025 and the benchmarking reports conducted by *Volvo*, it was possible to gather information on the busbar architecture of *Mercedes eActros 400*, which is a competitor electric truck along with several other electric cars such as *Volvo EX30*, *Hyundai Kona*, *Audi SQ6 e-tron*, etc. Although access to only images with limited details to the pertinent technical data was available, the authors were able to understand the concepts used in different products and key information such as the material used, the fasteners used, strengths and weaknesses along with the feasibility of using them in our case.

3.7.1 Patent search

Using ("Espacenet - European Patent Office", 2025) and classification search paths as "H01B17/18/low", "H01B17/005/low" or "H01B17/20/low", an overview of existing solutions could be compiled for reference to new ideas or what is currently used in different industries. Using search paths as presented above means using a classification search and filtering the patents to solutions that are relevant to the higher-level sub-problems from the *Function-Means Tree* or if there are other solutions that solve the entire problem directly.

As the previous paragraph suggests, the project started by investigating what earlier patents had discovered for electricity, electric elements, insulators, insulators, or insulating bodies characterised by their form. However, this category comprised several thousand patents, see Figure 3.5. From there, the authors selected relevant sub-categories shown in Figure 3.6 and iterated the perceived relevancy from there. This was done for the different sub-solutions presented in the *Function-Means Tree*.



cpc=H01B17/00/low

Home > Results > GB2473697A

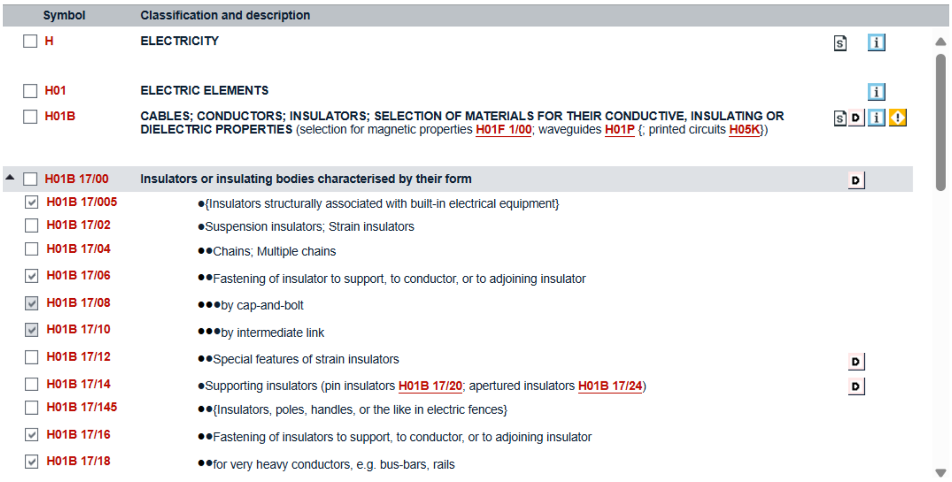
19 218 results found

List view: Text only

List content: All

Sort by: Relevance

Figure 3.5: Resulting number of patents before final screening categories were selected using ("Espacenet - European Patent Office", 2025).



	Symbol	Classification and description
☐	H	ELECTRICITY
☐	H01	ELECTRIC ELEMENTS
☐	H01B	CABLES; CONDUCTORS; INSULATORS; SELECTION OF MATERIALS FOR THEIR CONDUCTIVE, INSULATING OR DIELECTRIC PROPERTIES (selection for magnetic properties H01F 1/00; waveguides H01P {; printed circuits H05K})
☐	H01B 17/00	Insulators or insulating bodies characterised by their form
☑	H01B 17/005	•{Insulators structurally associated with built-in electrical equipment}
☐	H01B 17/02	•Suspension insulators; Strain insulators
☐	H01B 17/04	••Chains; Multiple chains
☑	H01B 17/06	••Fastening of insulator to support, to conductor, or to adjoining insulator
☑	H01B 17/08	•••by cap-and-bolt
☑	H01B 17/10	•••by intermediate link
☐	H01B 17/12	••Special features of strain insulators
☐	H01B 17/14	•Supporting insulators (pin insulators H01B 17/20; apertured insulators H01B 17/24)
☐	H01B 17/145	••{Insulators, poles, handles, or the like in electric fences}
☑	H01B 17/16	••Fastening of insulators to support, to conductor, or to adjoining insulator
☑	H01B 17/18	••for very heavy conductors, e.g. bus-bars, rails

Figure 3.6: Visualisation of one patent category search iteration. Tool credit: (“Espacenet - European Patent Office”, 2025).

3.8 Concept Generation

This project used a set-based approach to remain open to available possibilities by terminating unfeasible alternatives in order to make decisions as late as possible in the project. The concept generation assumes large-scale production as presented in Section 1.1. This justified the importance of lowering the cost per product. In addition, the use of the TVPDC as the benchmark component for the fixation solution required careful consideration of the constraints of packaging, casting design, and electrical properties for traction voltage.

The project team engaged in an iterative process and multiple concept generation sessions, supported by the literature for systematic exploration and feedback from senior design engineers. ”As a result of the external and internal search activities, the team will have collected tens or hundreds of concept *fragments*—solutions to the subproblems. Systematic exploration is aimed at navigating the space of possibilities by organizing and synthesizing these solution fragments.” (Ulrich et al., 2011a, Chapter 7, page 135).

The concept fragment generation unintentionally started when the problem of the project was mentioned the first time and iterated from there. The concept fragments and sub-solutions were successively transitioned into an understanding of how the problem could be solved from different angles and what components or sub-solutions might be used. In this project, the concept sub-solutions were added to the *Concept combination table*, or *Morphological matrix*, under their respective sub-function from the function decomposition i.e. *Function-Means Tree*, section 3.5.

3.8.1 Set-based Concurrent Engineering

Set-based Concurrent Engineering, SBCE, is used and developed by *Toyota*. Published in 1999, (Sobek et al., 1999) explains that the set-based approach to product development means developing a set of possible solutions and terminating the ”truly weak" concepts under the course of the development process. This enables developers to make engineering decisions as late as possible.

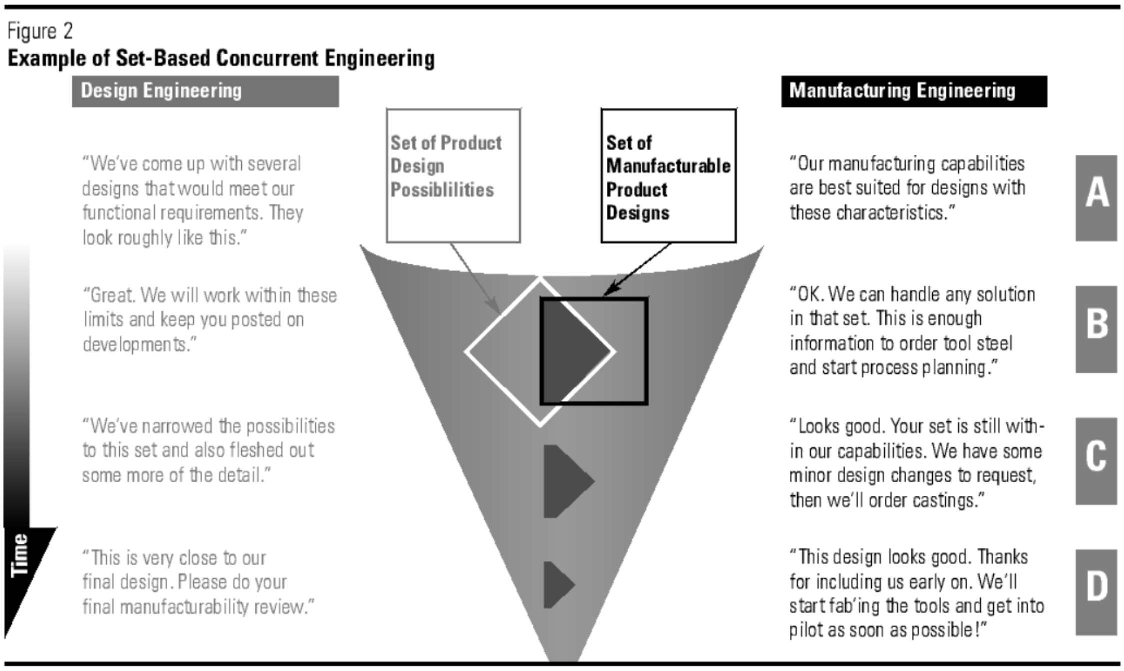


Figure 3.7: Set based approach explanation from (Sobek et al., 1999). Image taken from (1999).

For this project, the set-based approach is useful for making late decisions and allowing design iterations, feedback & knowledge, or even late "aha"-moments screen out the inferior concepts. An important feature for working this way is to include all engineering aspects from the start of product development. SBCE supports the method used in this project by incorporating the stakeholders (working engineers) of each step in the development loop over time, thereby adhering to developing feasible concepts. This is visualised in Figure 3.7 and can be linked to how the systematic approach of (Ulrich et al., 2011a) works by terminating infeasible solutions rather than "cherry-picking" what is believed to be the superior solution.

3.9 Morphological Matrix

The *Morphological matrix*, or *Concept combination table*, is a permutation table comprising combinations of solutions to sub-functions of the main solution while excluding all infeasible combinations of sub-solutions, resulting in a pool of all feasible solutions. If there are high quantities of sub-solutions and/or sub-functions the concept combinations are usually not sketched in detail but can be visualised through their distinctions in form of functions or shapes of bodies. The result of the table is referred to as the "starting set" in terms of SBCE, i.e. all solutions that are possible to develop.

3.10 Brainstorming Sessions

Brainstorming is a vital method to generate design concepts and conduct an internal knowledge search within a company. By bringing together cross-functional individuals, each with their own expertise and perspective, these sessions create a collaborative environment where a wide range of design alternatives can be explored. Relevant constraints, concerns, and insights from different disciplines are recognised early, improving both the quality and feasibility of concepts.

These sessions were also valuable for identifying opportunities and visions for a novel product in real time. The open, non-judgemental, and sometimes informal nature of brainstorming encourages participants to think creatively and share ideas freely. Immediate discussions often spark new concepts or lead to combinations and enhancements of existing ones, helping the product reach its maximum potential.

In addition, brainstorming supports iterative thinking and early visualisation. Ideas are often roughly sketched to explore how they might be realised. Although not all ideas may be feasible initially, even these contribute to the project's knowledge base and may inspire solutions down the line or in future projects. In general, brainstorming enables the generation of inclusive, innovative, and informed concepts by leveraging the collective knowledge of experienced individuals, in this project from within the company. This meant including as many areas as possible to cover manufacturing, assembly, cost, and general suitability for the environment inside the electric truck.

3.11 Concept Screening

The concept screening process is a practical and structured way to narrow down a wide range of ideas by identifying which concepts are infeasible or weaker when evaluated against defined criteria. Instead of relying only on judgement, this process involves comparing multiple concepts across key performance parameters such as volume, mass, simplicity of design, cost, and other user requirements. This helps ensure that decisions are based on objective reasoning rather than bias. In the end, concept screening helps to focus time and resources on the strongest candidates, setting a solid foundation for the next stages of development.

3.11.1 Elimination Matrix

The *Elimination matrix* is the first screening method for the output from the *Morphological matrix*. Here, the permutations are screened for all requirements in the technical requirements list until they either fail one requirement and are screened out, or pass all requirements and advance to the next screening method. The screening is done through intuition and understanding of the ingoing sub-solutions to the components and their characteristics. If uncertainty arises, the criteria are marked and noted, and the process continues. The mark is then revisited after the topic has been researched and the questions have been answered. All concepts are reviewed individually. For example, if volume is a requirement and one of the sub-solutions uses a concept that is certain to occupy more than the allowed value, all the concepts utilising that sub-solution will likely be screened out.

3.11.2 Pugh Matrix

The *Pugh Screening Method*, or the *Pugh matrix*, comprises a relative comparison of the output concepts of Section 3.11.1 against different reference concepts. This was done in iterations until convergence was reached or by average ranking after more than five iterations. The reference concept was initially set as the current benchmark and then as the previous best scoring concept for each iteration.

The number of iterations may vary depending on the number of concepts. However, for the robustness of the final concept score, the investigation aims to minimally use three to five iterations (if # concepts allow). The final iteration scores from the iterations are noted for the concepts to a final score where the least feasible concepts are screened out. If multiple concepts have the same or similar accumulated scores, their ranking averages can be used as a second reference for screening.

3.12 CAE

Computer Aided Engineering was used to evaluate and verify concepts and their functions. For this project, the team was provided access to *Chalmers* and *Volvo's* software and thereby decided to use:

- *Creo Parametric* for the construction of concepts.
- *Granta Edupack* for investigating material candidates that could meet potential requirements.
- *Ansys Mechanical* for analysing performance parameters in a structural context.

3.12.1 CAD - Creo Parametric

After sketching concepts throughout the concept generation phase, they were constructed into concrete solutions using *Creo Parametric* ("Creo Parametric 3D Modeling Software", 2025). *Creo* is a parametric 3D CAD modelling tool provided by PTC that helps engineers design a desired geometry in less time. It also uses a PLM system, where engineers can access relevant parts, which supports cross-functionality of various departments and provides appropriate information on each step to improve the communication loop. The authors got access to the TVPDC assembly CAD file with the current solution, which further helped to evaluate the size and volume occupancy of the fixation and how it affected the entire assembly. Navigating the product in the assembly CAD file proved insightful, as this became a key step in the realisation that there was unutilised design space underneath the busbar.

With the help of basic functions for solid modelling in *Creo*, plenty of design concepts were constructed and reviewed. It was an iterative process to come up with solutions that were realistic and feasible to manufacture and assemble. The authors also understood the problems during the creation of the models and provided insight to clashes with other parts. This step enabled the realisation of dimensions that proved to be critical, especially creepage and clearance. The new concept models were further structurally analysed, explained in Section 3.12.3.

3.12.2 Material Research - Granta Edupack

In order to find materials that would be suitable and beneficial for our case, a thorough material investigation was carried out using *Granta EduPack*. This tool contains extensive material databases with a wide range of properties, including mechanical, electrical, thermal, and many more. These materials are further classified into categories such as metals, polymers, ceramics, and composites, making it easier to explore and compare material properties with other relevant options within that material group.

The selection process begins with the application of filters based on specific criteria relevant to the application, such as the yield strength and the dielectric strength. The initial criteria analysed for insulation were dielectric strength and mechanical strength, later, material price was also used to justify the cost-efficiency. Screening values were obtained through derivation of forces from different loads as initial screening values, these were revised later.

Materials that met all the minimum/maximum conditions required were then further analysed using *Ashby charts*, which help to graphically compare different materials based on the desired material indices and performances. These charts provided a clear visual representation of material trade-offs, enabling a better understanding of how different materials perform relative to each other.

This methodology provided a structured and data-driven option of screening and choosing materials. In addition to simplifying the process of comparing material qualities, it also improved the quality of decision making by striking a balance between feasibility, performance, and cost.

3.12.3 Structural Analysis - Ansys Mechanical

Ansys Mechanical is a widely used CAE tool that can analyse and evaluate complex structures using meshes and the finite element method. It was used to analyse and visualise the performance of the concepts during the different load cases from the requirements and testing standards, which can be found in Section 4.7.4. Initially, this was performed to ensure mechanical robustness and that the design analysis did not show any unexpected signs of weakness for the failure modes presented in Section 2.4.

3.13 Concept Gate

The *concept gate session*, or *mid-term presentation* in the context of this thesis marked an important checkpoint in the development process. It took place once the initial design was shaped through research and knowledge from the engineering team in the TVSD department. The concept gate gave the authors the opportunity to share and reflect what has been developed so far with others for input and feedback.

The presentation covered the background of the problem, the reasoning behind the approach taken, and the initial design results. It was shared with engineers from the TVSD department, who brought valuable technical insight and practical experience. The aim was to clearly communicate the challenge and the design thinking that had guided the work up to that point.

More importantly, the session was conducted to spark discussion and start the internal dialogue on potential future implementation. By presenting the work in progress, the authors hoped to invite different perspective questions, ideas, and suggestions that might not have been considered before. Fresh insights were especially valuable at this stage, when the design was still under early development and less decisions had been taken, this meant flexibility for changes in the design.

After the session, the feedback received was reviewed and used to refine the concept. Some aspects of the design were adjusted or rethought based on input. In the final presentation, the updated concepts were again shared with the audience who provided initial feedback, helping to ensure the project continued to move in the right direction and aligned with the needs and expectations of the engineering team. This would, hopefully, increase the probability that it is valuable and relevant in future projects.

3.14 Detailed Design

Product development projects are iterative processes, which means that concepts are thoroughly examined to identify and address areas for modification over the course of the project. The iterative process was used to progress the concepts with the input of the engineers interviewed who interpreted the solution with respect to their area of expertise and communicated to the authors about the fulfilment of their needs. This feedback helped refine the design with realistic insight into material properties, design features, or input for easier assembly or maintenance. However, this process alone did not guarantee the fulfilment of the requirements in the testing but merely indicated that people who had experience with the testing believed that the concepts would perform superior to the benchmark today. For *Volvo's* future busbar fixation concepts, this step was beneficial in defining recommended ranges (or value intervals) for certain characteristics of the solution to make sure they met both technical requirements and practical needs. Furthermore, this made the solution practical and reliable while providing the ease of alteration.

For support, CAD and CAE (described in Section 3.12) were extensively used to translate the concept into concrete solutions that worked in harmony with other components of the TVPDC. These tools not only helped visualise and validate the design, but also reduced the need for repeated physical prototyping, saving both time and resources.

4

Results

The results are presented in chronological order of the process of the project which is profoundly based on the product development process suggested by (Ulrich et al., 2011a). Because of the confidentiality of treated content, information and details cannot be disclosed; however, the chapter will comprise material such as the thought process that went into the development of the solution and what knowledge was extracted from the different phases of the process.

4.1 Initial knowledge search

Initial meetings laid the ground for an early investigation of the current solution. The information provided insight into characteristics of the current solution; however, the manager stressed the need not to give the project an early bias and, therefore, did not want to share the details of the current solution the engineering team was working on.

The initial understanding of the problem and the search for information yielded areas of interest for concept development. Further investigations were necessary to find a basis to determine whether these areas are roots of cause for a non-ideal solution, or if it is the implementation rather than the concept itself. This provided an opportunity to delve deeper into an evaluation and testing/analysis of the current solution.

Deeper understanding was achieved by the engineers explaining the function they want the solution to provide along with navigating the CAD software (having ”no bias” in mind) to show the reference product where the solution operates to give context to some realities present in the problem statement.

The project team used this information to draft a ”problem understanding” document where all new learnings were recorded in the form of *Microsoft Powerpoint* slides. This document would prove useful in documentation of the internal understanding, knowledge stream, of the team and how it evolved along with the project, how stated the knowledge or question and when it was stated. From the *learnings* document, the learnings could be used as a base to form relevant questions on the topic for the subsequent steps of the development process.

4.2 Interviews

While conducting the interviews, the authors began investigating the option of considering several sub-systems as parts of the ”super-system” of fixating the busbar to the casting, this implied including questions about component dependence and relations in the TVPDC. The investigation continued to the *Customer needs identification* where it was passed to the final specifications-stage, Section 4.3. There, the super-system idea was halted because of time constraints and project scope. After reflection, the authors concluded the perceived value of investigating the relation of the different sub-systems in the context of busbar fixation would be beneficial in a rapidly changing environment and for possible future scenarios. Ultimately, this idea proved useful in the accumulated understanding of the system and possibly provided vital understanding of what came to be the final concepts of this project.

4.3 Customer Needs Identification

The documented answers from the interviews were analysed and sorted into groups of component problem and its occurrence. The groups were created as the project at the time treated several sub-systems that together formed the busbar fixation super-system. The full system comprised: fastener, busbar, TIM and housing. The hierarchy of the needs formed the *Needs Statement* according to Section 3.3.1. After evaluation and reflection, the scope was reduced to focus on the development of the fastener (as mentioned in Section 4.2) as it comprised the main functionality on fixing the busbar to the cast.

Further, given the time constraint of the project, the authors did not want to risk underperforming the initial task and made the decision into place the focal point on the fixation. The reflection concluded that this was a part of the iterative process and the nature of product development project. Table 4.1 shows redacted needs statements for the fastener without corresponding importance factor and metric. After every process step, the results and process were reflected and evaluated according to (Ulrich et al., 2011a).

Nr.	Fastener needs statement
1	The fixation materials have good electrothermal strength.
2	The solution allows for use in multiple Volvo components.
3	The solution provides robust busbar clamping over time.
4	The fixation materials have low, or no creep over time.
5	The solution uses low volume around the busbar.
6	The solution is compliant to vibration-, shock- and thermal profile.
7	The fixation force of the busbar is provided by the fastener.
8	Eventual anti-rotation feature is robust to forces created by assembly impacts.

Table 4.1: Derived fastener needs statements based on interviews.

The statements have been somewhat ”generalized” for the public report. To protect internal needs, the frequency and importance of the needs are excluded.

Subsequently, the target specifications are meant to be established. In the company, this is done through breaking down the requirements for the full product and from there, iteratively, breaking down the requirements for each component in the component hierarchy. Given the confidentiality of this information and the accessibility for the project to this information, this was achieved using industry standards for commercial electrical vehicles (found in Section 4.7.4) and breaking them down into technical requirements. For quality assurance, the requirements were multiplied by an undisclosed factor of safety.

The final specifications were established later in the project, at a lower uncertainty. However, the robustness of the design and the uncertainty of potential future implementations of the solution justified the use of ranges instead of precise values. This enables the implementer to adjust the details according to their specific needs and design space according to the project task. Some ranges imply a trade-off between different characteristics or between advantages and disadvantages for the alternatives. These are provided in the recommendation for the *Volvo* internal documentation & report.

4.3.1 Customer Needs Importance

The needs were ranked for importance according to the authors' perception of the relative weight of each need to fasten the busbar while isolating its electricity from the main housing.

Nr.	**Needs importance ranking**	**Imp.**
1	The fixation materials have good electrothermal strength.	5
2	The solution allows for use in multiple Volvo components.	2
3	The solution provides robust busbar clamping over time.	5
4	The fixation materials have low, or no creep over time.	5
5	The solution uses low volume around the busbar.	3
6	The solution is compliant to vibration-, shock- and thermal profile.	5
7	The fixation force of the busbar is provided by the fastener.	4
8	Eventual anti-rotation feature is robust.	2

Table 4.2: Fastener needs importance ranking.

The ranking was inspired by the way the team understood the problem along with influences from the core values of the company, presented in Section 1.1.

In addition, the interviews resulted in specific values that the team could learn from and aim to achieve. Furthermore, given the task: ”investigative concepts”, the needs were kept short and used as a guide to stay within the scope and to generate relevant and valuable solutions.

4.4 Function-Means Tree

The *Function-Means Tree* (Figure 4.1), and, in extension, the function decomposition, comprises the iterative process of understanding and adapting the solution to the problem. To gain nuanced understanding, the project team created separate documents in which the problem and functions were broken down and analysed. As the project gained more knowledge, these documents were iterated and updated. For the complete function-means tree, see Appendix C. This stage marks the start of the concept generation phase and initial clarification of the problem (Ulrich et al., 2011a).

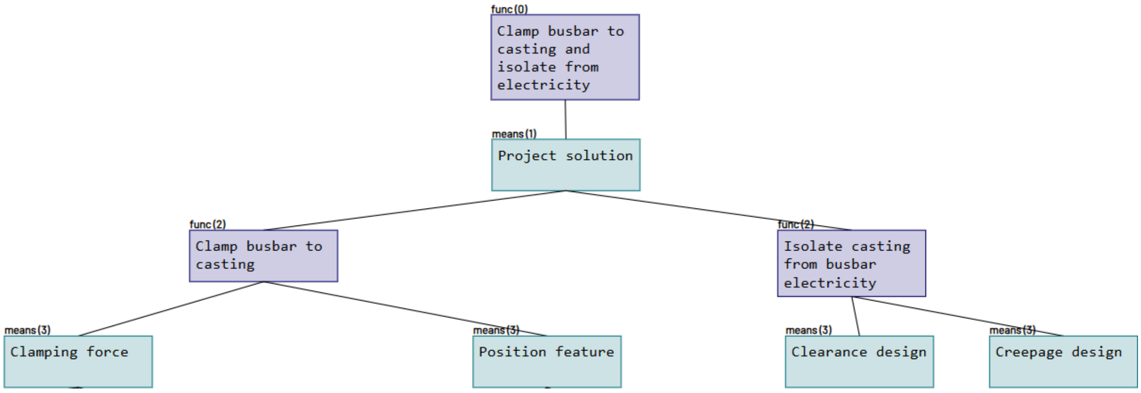


Figure 4.1: Function-means tree. Tool credit: (“Trinity”, 2025)

This meant clarifying the problem through decomposition of complexity into simplicity. The project achieved this by focusing on the critical sub-problems of ”Clamp busbar to casting” and ”Isolate casting from busbar electricity”. These functions were seen as the two roots to the problems and were used as main questions to answer when searching for external knowledge, patents, and when benchmarking.

It was known that the functions could be achieved separately. With this understanding, the authors used the knowledge of the component packaging situation in the TVPDC and external sources for inspiration and information. The cross-sectional design space was analysed and some areas were concluded to provide more design space than others. In addition, internal discussions among the authors based on the cross-sectional view of the current solution led to the opinion that the insulation method could be optimised.

4.4.1 Enhanced Function-Means Tree

After the interviews and after examining and decomposing the problem and functions, a super-system understanding was constructed. The knowledge that the authors had collected pointed to that TIM and fixation were two variables strongly dependent, as seen in Figure 4.2. From delimiting changes in the busbar design and knowing from the interviews that design space existed over and under the busbar, the authors quickly concluded that the system would greatly benefit from disconnecting the system's dependence on the TIM. This could be done by a change in the approach and design of the fixation.

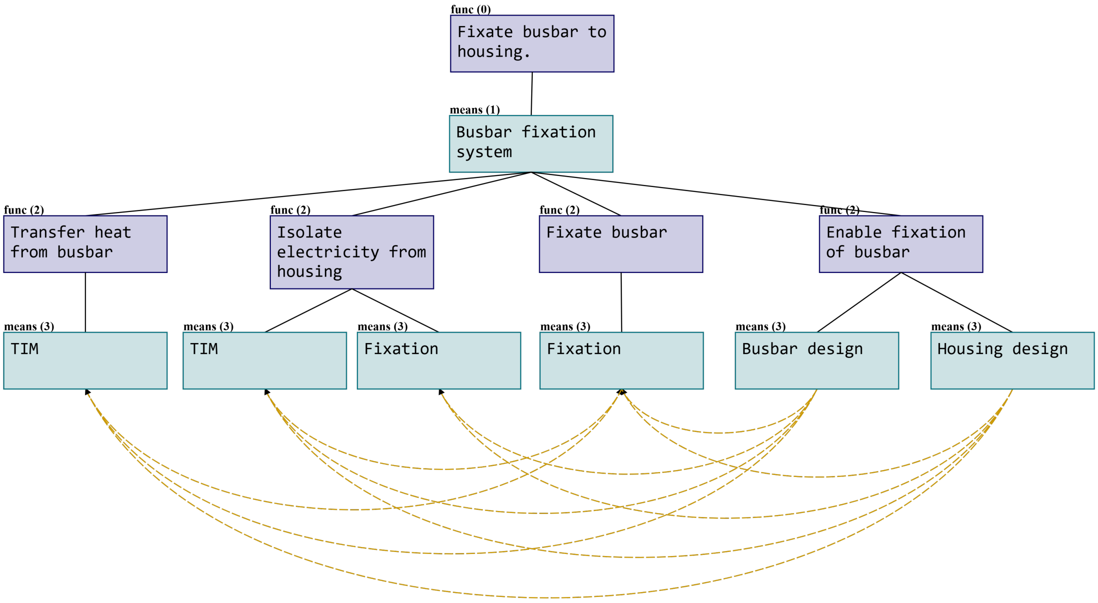


Figure 4.2: EF-M modelling interpretation on the dependencies in the super-system. Tool credit: ("Trinity", 2025)

By examining and locating multiple "two-way" dependencies, the authors concluded that in an ideal system, the sub-systems would be independent or minimally inter-dependent on few sub-systems. From this, it was extracted that something needed to protrude towards the clamping means, and thereby eliminate the material creep located in the insulating material or creeping material.

Inherently, the same or some other means were needed to insulate the electricity from the busbar while the device was clamped to the housing. After reviewing the demands and screening materials in *Granta*, it was decided that two materials would increase the feasibility of solving the problem within the delimitations.

4.5 Concept Classification Tree

The development of the function-means tree helped guide the authors to consider as many solutions as possible for each function by defining general function names. As suggested by (Ulrich et al., 2011a), a concept classification tree was generated based on the primary functions expected by the product, one of which can be found in Figure 4.3.

The primary functions identified were to isolate the housing (casting) from the busbar electricity and to secure the busbar to the housing. These functions were further categorised into various potential solutions following the process of the figure, leading to the identification of multiple fragments. In order to arrive at these fragments, brainstorming, research, and exploration of numerous solutions were used as main search methods. In total, this further improved the understanding of the problem.

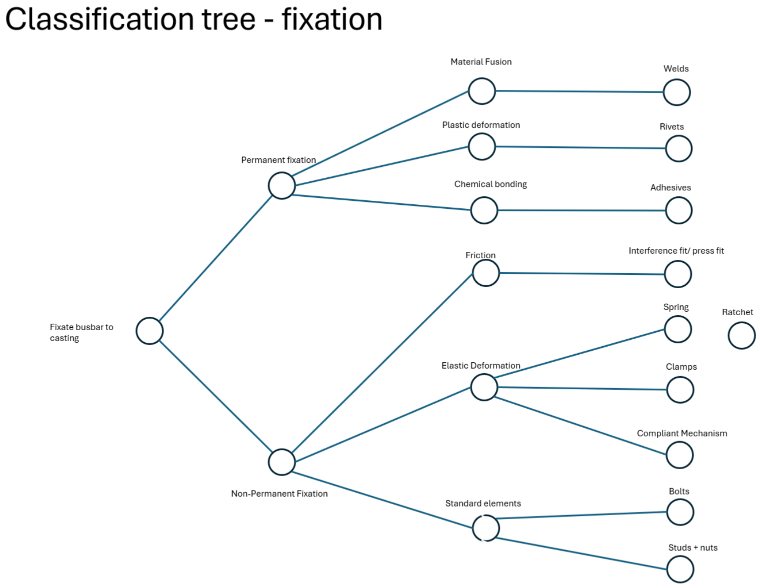


Figure 4.3: Classification tree visualization for fixation alternatives.

Apart from the primary functions there were also two more functions that governed the overall design, i.e. the cooling method and the type of busbar to be used. Owing to the delimitations in Section 1.5, active cooling with non-insulated busbars was continued accordingly after agreement with *Volvo*.

4.6 Benchmarking

The project used the *Mercedes E-Actros 400* power distribution unit as a reference for the TVPDC and competitor benchmarking. Images of their PDU gave insights on how the busbar and other electrical components were secured for that truck as shown in Figure 4.4.

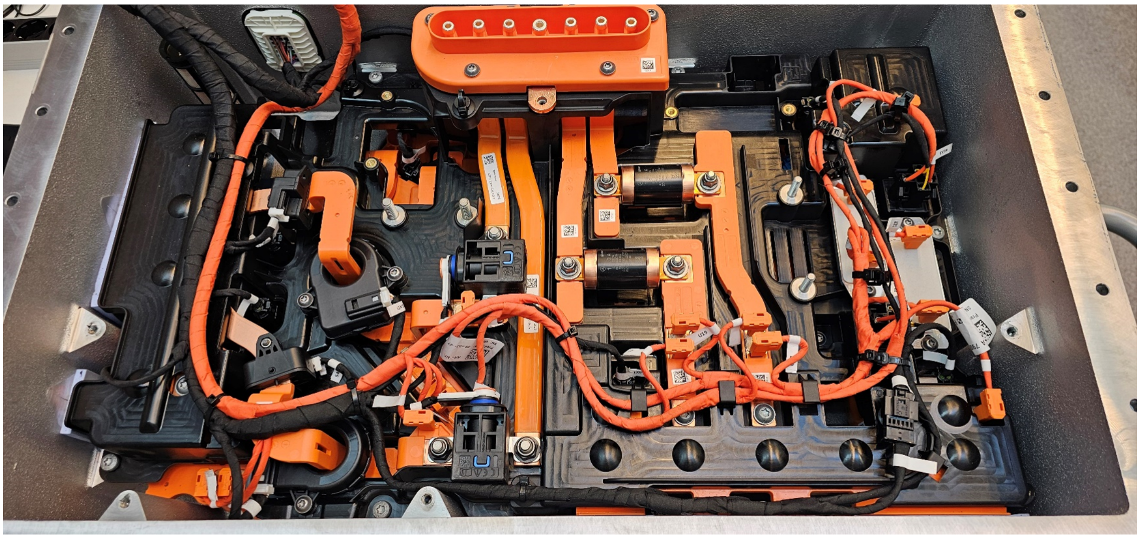


Figure 4.4: Power Distribution Box of *Mercedes E-Actros 400*. Credit: *Volvo*

However, the resources of the project allowed only a brief investigation of the characteristics of the components and choices of other engineering teams rather than performance comparisons and materials analysis. Starting with the busbar itself, they were made up of copper and quite heavy. Figure 4.5 shows that the busbars used have a plastic enclosure made with the material PA66-PA6-GF15-HI to isolate it from electrically conductive paths. This plastic enclosure or jacket seem to have a snap functionality for easy and quick assembly. Furthermore, they have metal inserts on either side of the busbar on the enclosure which is used to fasten it to the aluminium casting with the help of bolts. These busbar bolts and contactor bolts used loctite or threadlocker to secure the bolts in the tapped hole.

(a) Fixation of insulated busbar

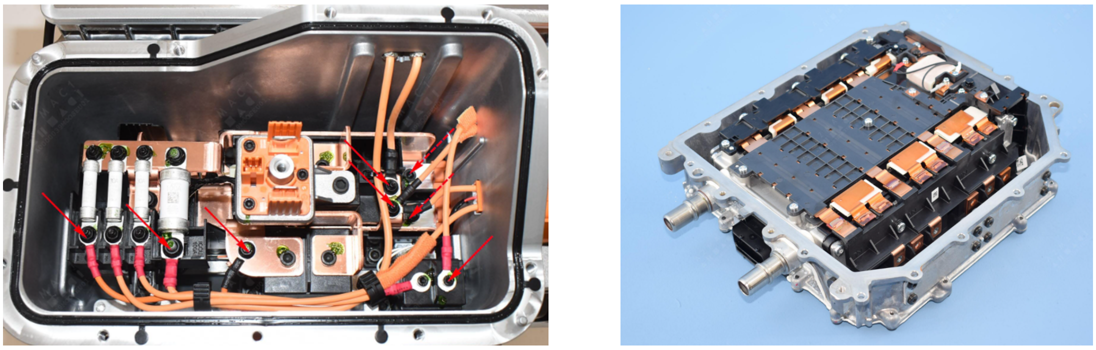
(b) Insulated jacket concept

Figure 4.5: Busbar and fixation concept used in *Mercedes E-Actros 400*. Credit: *Volvo*

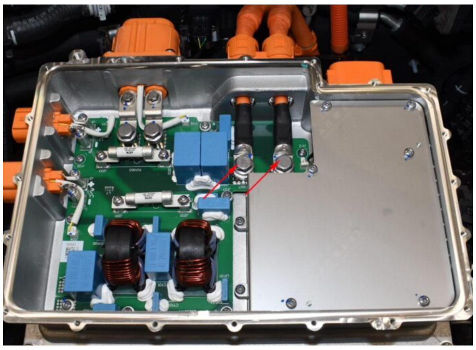
The aluminium mould acted as a heat sink which had cooling channels beneath it that dissipated the heat generated by the busbar. TIM pads were used between the busbar and the casting for effective heat transfer; however, the cooling was only limited to 4 larger busbars instead of all. Another observation made was that some busbars had expensive coatings instead of plastic jackets. This approach of *Mercedes* had merits but at a cost of few disadvantages, such as increased volume occupancy and higher manufacturing cost due to multiple unique parts. These were a major driving factor for this thesis, but were still considered to contribute to the knowledge pool on the power distribution system.

The authors accessed the benchmarking portal for automotive industry, *A2MAC1*. Although the assets for electric trucks were limited, the team compared the high voltage architecture of several commercial electric cars such as *Hyundai Kona*, *Hyundai Ioniq 5N 2024* and *Volvo EX30*(“A2MAC1”, 2025). Since these cars have lower requirements compared to that of a truck, they had smaller and more compact PDUs.

As shown in Figure 4.6 both the *Hyundai*’s comprise of copper busbars and rely heavily on plastic brackets and supports which are packaged in aluminium enclosures. This trend was observed in almost all cars, as the busbars are comparatively much lighter and compact. In addition, the mechanical loads and requirements according to standards are more relaxed for commercial passenger vehicles compared to those of heavy trucks, proving this type of solution more effective. Lastly, *Volvo EX30* had the approach of using HV PCBs as they prove to be space efficient for smaller distributions.



(a) *Hyundai Kona* PDU **(b)** *Hyundai Ioniq 5N* PDU



(c) *Volvo EX30* PDU

Figure 4.6: Benchmarking images from A2MAC1

4.6.1 Patents

After examining closer on patent databases *Espacenet* and *Google Patents* from categories ”*H01B 17/18*” (Electricity -> Insulators or insulating bodies characterised by their form -> for very heavy conductors, e.g. busbars, rails), the team concluded that no similar solutions were documented as patents in recent time.

The team decided that the team’s own brainstorming would provide the best result, since the search did not provide inspiration for new concept sub-solutions or complete system solution.

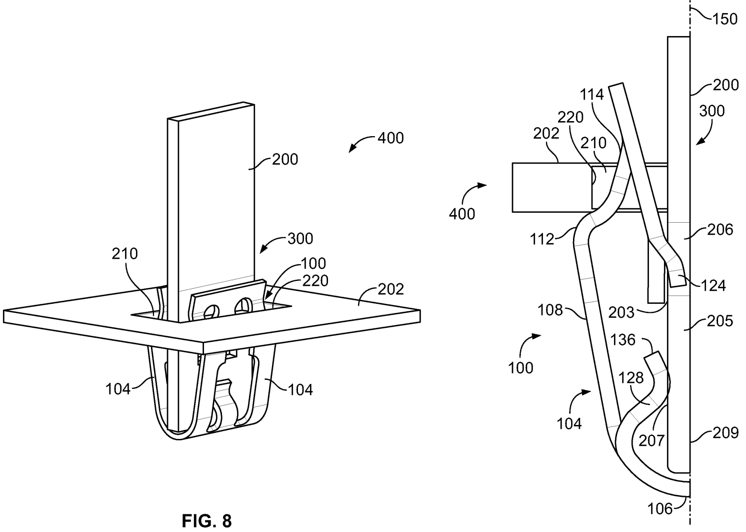
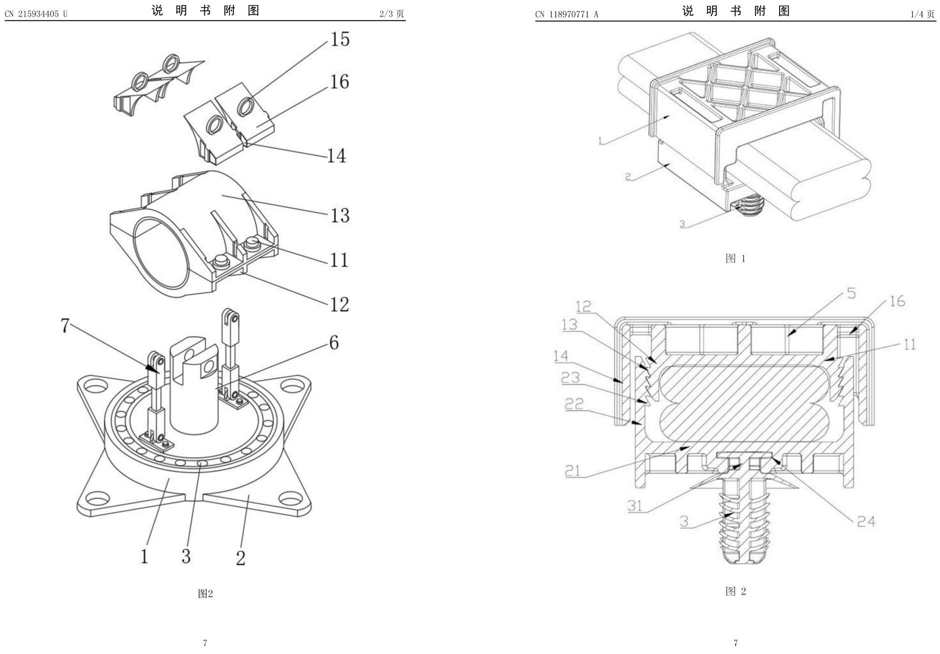


FIG. 8

FIG. 9

Figure 4.7: Compliant mechanism used for snap-on feature (Bidlake et al., 2021).



(a) Clamping mechanism used in busbar fixation (Shaohua & Yan, 2021).

(b) Compliant mechanism used for busbar fixation (Maike et al., 2024).

Figure 4.8: Patents for existing fixation alternatives.

The search could, however, provide drawings of existing fixation concepts that visualize better on how *compliant mechanism* or *clamp* could be implemented in similar applications. The patents in Figures 4.8 and 4.7 were helpful in understanding how busbar fixation solutions are developed and used by professionals around the world.

4.7 External Knowledge Search

The interviews provided valuable information for understanding where to look for inspiration for the current solution and, extensionally, where it could potentially be beneficial to search for information to add to the knowledge value stream. Ideally, this information would be new, novel and add value to the understanding of how to fixate mechanically, isolate from electricity while enduring cyclical thermal and vibrating loads.

4.7.1 Cooling Nut by Nissan

In a similar environment, but for different applications, (Ishii et al., 2022) sought for and succeeded in downsizing and reducing the weight of the case for a traction inverter. This was done through the development of a resin water jacket case seen in Figure 4.9. Because the traction inverter now used a plastic jacket instead comprising of aluminium, the team had to dissipate heat from the busbars (extension of: lead away heat from the DC capacitor and power module) using some other method. This led to the development of the *busbar cooling nut*, a cast aluminium part molded in resin to isolate electricity leakage while dissipating heat from the busbar into the aluminium shield plate.

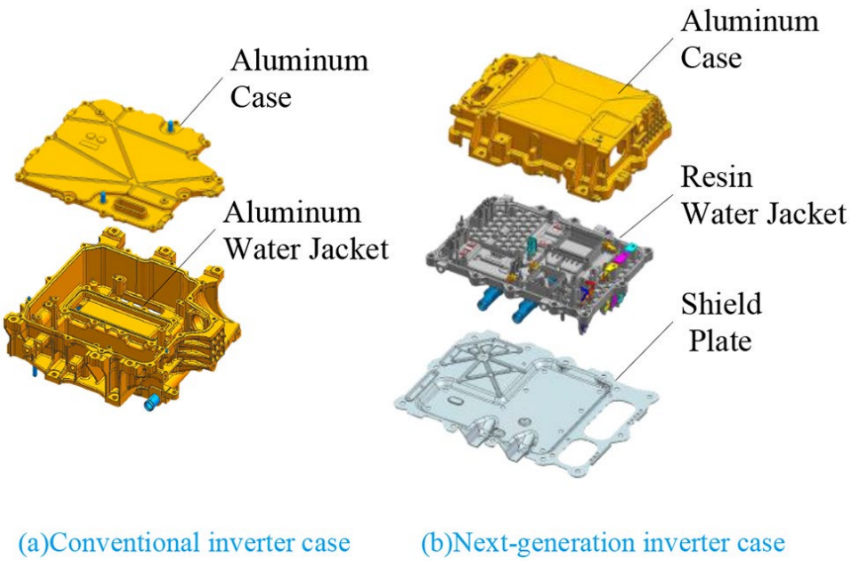


Figure 4.9: Overview of (Ishii et al., 2022) old and new inverter case.

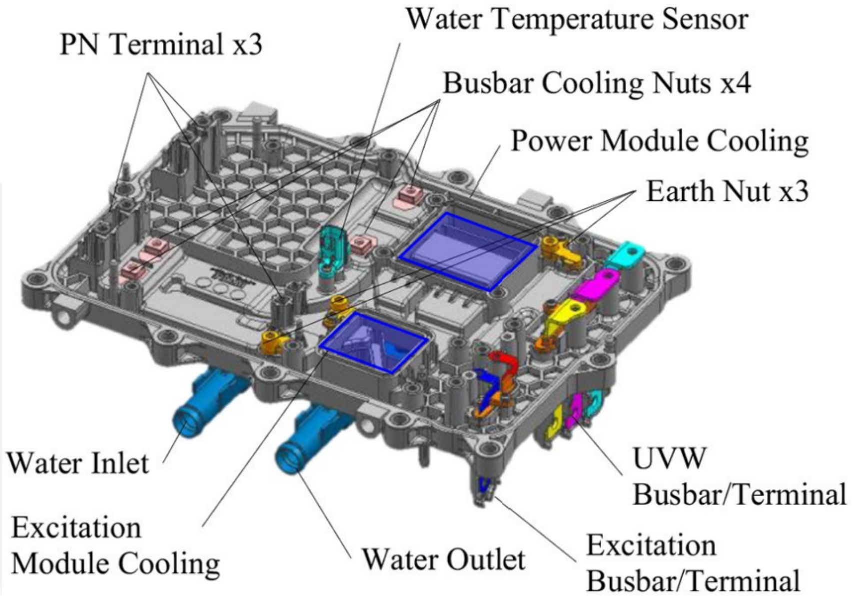


Figure 4.10: A closer view on the (Ishii et al., 2022) water jacket and the context for the *busbar cooling nuts*.

The busbar has a pin-fin structure to secure it to the water jacket while providing sufficient surface area for dissipating heat through the cooling channel. Figure 4.11 shows the heat path from the DC capacitor and power module. It provided inspiration and understanding of feasibility of manufacturing for large-scale implementation.

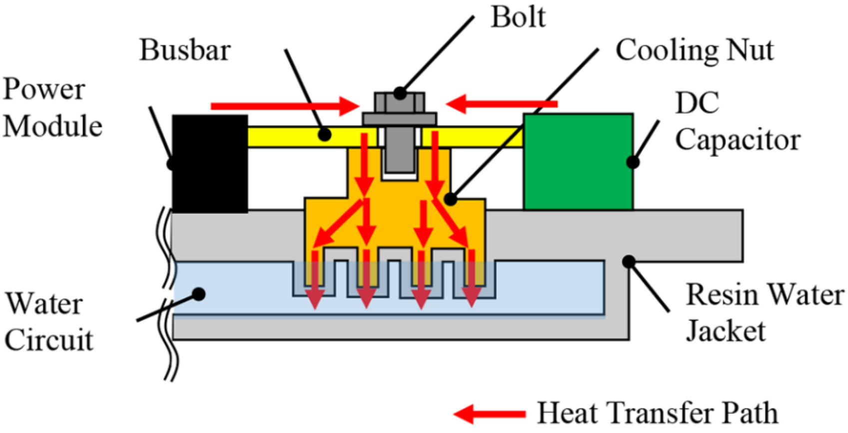


Figure 4.11: Heat path visualization for inverter components. Credit: (Ishii et al., 2022)

Figure 4.11 widened the view of how electrical insulation could be achieved. For the case of TVPDC however, the conditions would be different but the idea of resin coated insulation was considered an interesting topic for investigation.

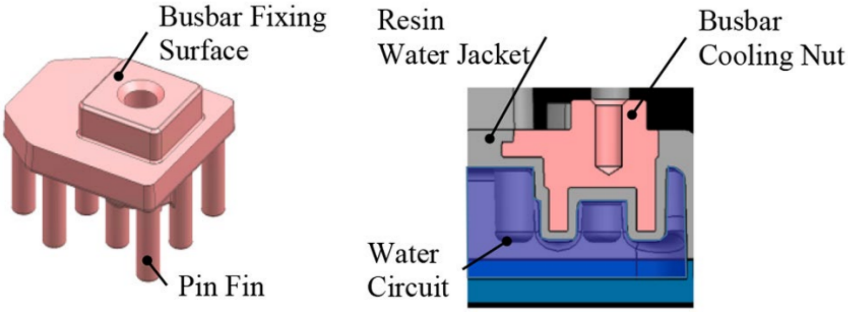


Figure 4.12: Isometric view of busbar cooling nut and in assembly context on water jacket. Credit: (Ishii et al., 2022)

4.7.2 Material Characteristics

The thesis base is mechanical design engineering, together with the problem description and the information gathered in the interviews (Section 3.2), the team initiated searching externally and internally for material knowledge. The search comprised a list of common material characteristics and values used in the commercial automotive industry, together with ISO standards requirements, Section 4.7.4, this provided direction to what materials could be considered *feasible* with their performance with respect to the cost and manufacturing aspect.

From the function-means tree, Section 4.4, the team understood that the solution material composition would comprise of one of *two* possible material characteristic combinations:

1. Solution is insulated and clamped by one material
2. Solution is insulated and clamped by different materials

The different alternatives implied unique challenges and benefits, where the first alternative meant stricter material requirements and therefore the screening of materials to find a suitable option. The latter option was more ”open” and relied on finding a design that would perform the two functions separately. No alternative was screened out; however a list of material requirements solutions was compiled for future material screening and was used as a base for different cost and manufacturing scenarios for eventual future implementation.

These initial requirements or characteristics of the material as shown in Table 4.3, are directly related to the demands of the mechanical design of the solution. This required the solution to have a material that had high strengths in relative direction of loading, excellent electrical insulating properties, and long service life which were a must.

In addition, low cost, easy manufacturing method, and decent thermal conductivity would be a plus point. External searching was used to find an understanding and ”aim” for what values have been used for these material characteristics in similar application before. This was further aided by the insights from Section 4.6 shedding light on materials used in the automotive sector. The information was documented for screening of materials with *Granta EduPack* (“Ansys Granta EduPack”, 2025).

Characteristic	**Unit**
Yield strength	[MPa] or $[\frac{F}{A}]$
Shear strength	[MPa] or $[\frac{F}{A}]$
Dielectric strength	$[\frac{V}{m}]$
CTI	[-]
Long-time service temp.	$[^oC]$
Thermal conductivity	$[\frac{W}{mK}]$
Material Price	[SEK]
Manufacturability	[-]

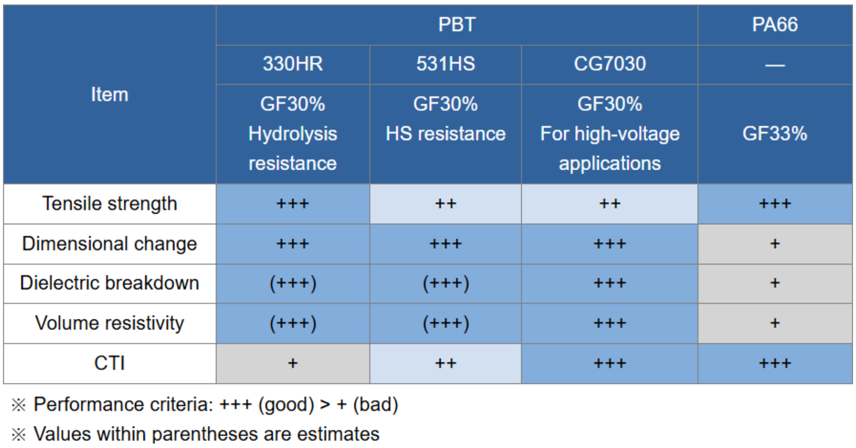
Table 4.3: ”Ballpark” of material characteristics for clamping and insulating busbar.

The above material characteristics were then used in the selection of materials in *Granta*. The Method and Results of using *Granta EduPack* can be found in Sections 3.12.2 and 4.7.3.1 respectively.

4.7.3 Material Investigation

Following the interviews and the creation of the function-means tree, a material search was conducted to map contenders to fill the main functions. The investigation started with searching the Internet for similar applications in the commercial automotive industry and later screening material database *Granta Edupack* for materials that had been overlooked or missed during the initial search.

In an article on comparing the electrical properties of *PA66* and *PBT*, *Polyplastics.com* summarises that " since the properties of the *PBT* grades experience little change even in hot and moist environments, we can determine that they are more suitable than PA66 for use in high-voltage environments" (Polyplastics, 2020).



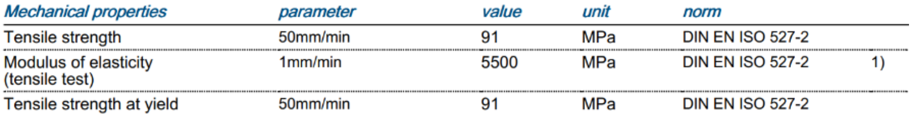
Item	PBT			PA66
	330HR	531HS	CG7030	—
	GF30% Hydrolysis resistance	GF30% HS resistance	GF30% For high-voltage applications	GF33%
Tensile strength	+++	++	++	+++
Dimensional change	+++	+++	+++	+
Dielectric breakdown	(+++)	(+++)	+++	+
Volume resistivity	(+++)	(+++)	+++	+
CTI	+	++	+++	+++

※ Performance criteria: +++ (good) > + (bad)
※ Values within parentheses are estimates

Figure 4.13: Comparison of resin materials for high voltage resistance (Polyplastics, 2020).

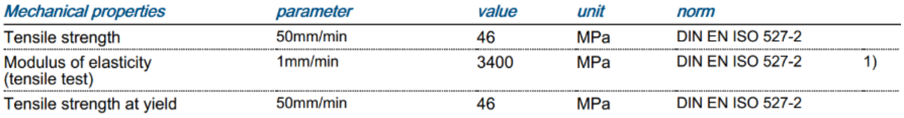
By looking at the table and comparing *PA66* and *PBT CG7030*, there is a trade-off in mechanical strength and electrical strength for the materials, depending on the specifics for the use case in the electrical truck for *Volvo*, both these materials could be considered useful. By comparing the yield strength of the materials provided by *Ensinger Plastics* (found in Figures 4.15 & 4.14), there is a marginal difference where PA66 obtains the highest value of 91 MPa while the yield strength of PBT is lower at 46 MPa.

Depending on the final requirements of electromechanical and electrothermal loads, this could be a deciding factor for the material to be chosen. If the yield strength proved to be not a problem, a material with superior electrical properties could allow for a downsized, lighter final product. However, cost and manufacturing attributes must be taken into account. For material data sheets, see Appendix E



Mechanical properties	*parameter*	*value*	*unit*	*norm*	
Tensile strength	50mm/min	91	MPa	DIN EN ISO 527-2	
Modulus of elasticity (tensile test)	1mm/min	5500	MPa	DIN EN ISO 527-2	1)
Tensile strength at yield	50mm/min	91	MPa	DIN EN ISO 527-2	

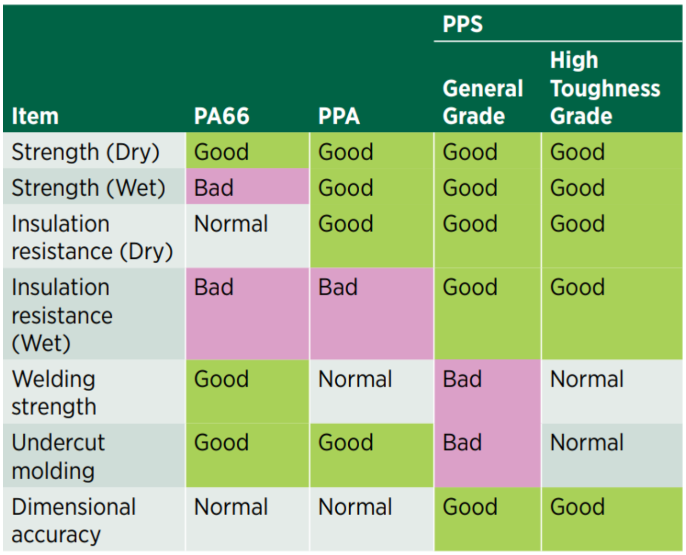
Figure 4.14: Mechanical data snippet from Appendix E.1.



Mechanical properties	*parameter*	*value*	*unit*	*norm*	
Tensile strength	50mm/min	46	MPa	DIN EN ISO 527-2	
Modulus of elasticity (tensile test)	1mm/min	3400	MPa	DIN EN ISO 527-2	1)
Tensile strength at yield	50mm/min	46	MPa	DIN EN ISO 527-2	

Figure 4.15: Mechanical data snippet from Appendix E.2.

(Ishii et al., 2022) provides information on materials that could be investigated for a similar application in this project and thereby provide a basis for justification on proof of function for the usage environment.



Item	PA66	PPA	PPS	
			General Grade	High Toughness Grade
Strength (Dry)	Good	Good	Good	Good
Strength (Wet)	Bad	Good	Good	Good
Insulation resistance (Dry)	Normal	Good	Good	Good
Insulation resistance (Wet)	Bad	Bad	Good	Good
Welding strength	Good	Normal	Bad	Normal
Undercut molding	Good	Good	Bad	Normal
Dimensional accuracy	Normal	Normal	Good	Good

Figure 4.16: Material comparison based on performance requirements (Ishii et al., 2022).

The investigation found different values for the CTI of the same material, leading to suspicion and reading the information with caution. The variation in CTI values could depend on different testing methods or environments; however, none were specified; therefore, the results were taken with caution and the interpretation that the value was in a range and not a precise number when performing calculations in later stages of the project.

Furthermore, as a result of the search, automotive material characteristics/properties were used as a reference to compare and elaborate the material characteristics. In the context of electromechanical strength, some parameters are presented in Figure 4.13.

4.7.3.1 Material Search in Granta Edupack (Insulating Material)

To further broaden the perspective on viable materials for the task, a parametrised material search was conducted in *Granta Edupack*, hereby *Granta* ("Ansys Granta EduPack", 2025). In the search, different material databases were screened by filtering for the minimum values allowed according to the project calculations.

The materials were then charted on different graphs in which the authors visualised the relative strength of the materials using the *yield strength* as the Y axis and the *dielectric strength* as the X axis for an initial comparison. Given the industrial scale of the trucks operations, the X and Y axes were changed to Yield strength/Price and Dielectric strength/Price for stating an early feasibility incentive to justify the material economically given its performance.

Granta provides several material databases also referred to as the ”Material Universe” and a comprehensive menu with parameters and characteristics to screen materials. After comparison based on the appropriate value ranges for the characteristics mentioned in Section 4.7.2, the plastics database was chosen for a more detailed search. Figure 4.17 shows the relative performance between materials that passed and highlights the subgroup *plastics*. It also shows the materials which are grey in colour that did not meet all the requirements. By this performance overview, the plastic material database indicated an advantageous starting point.

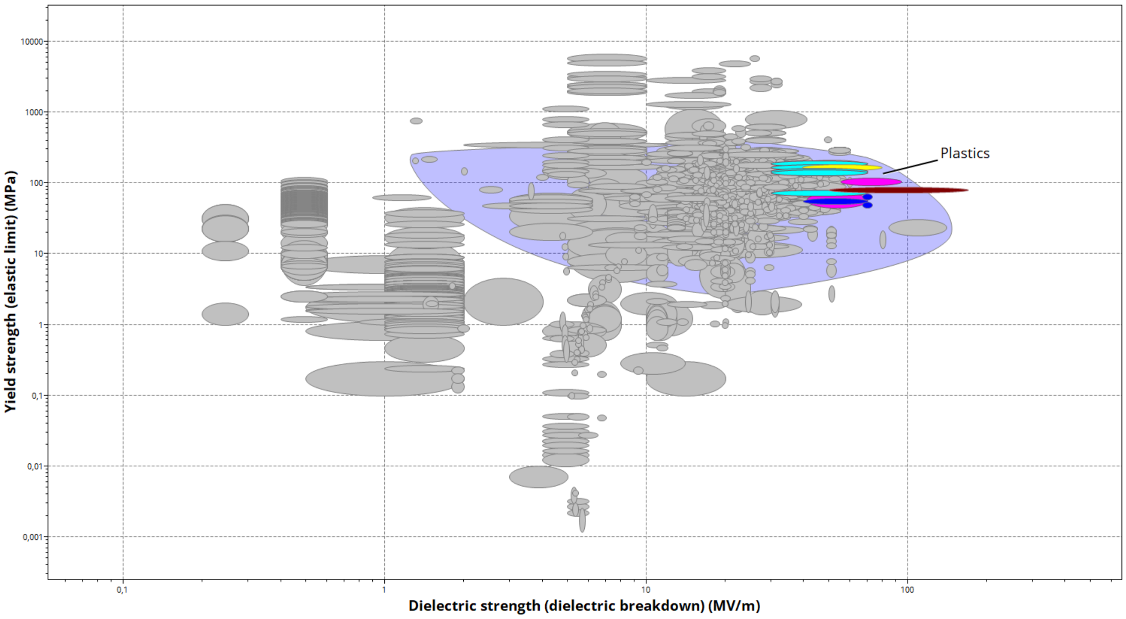
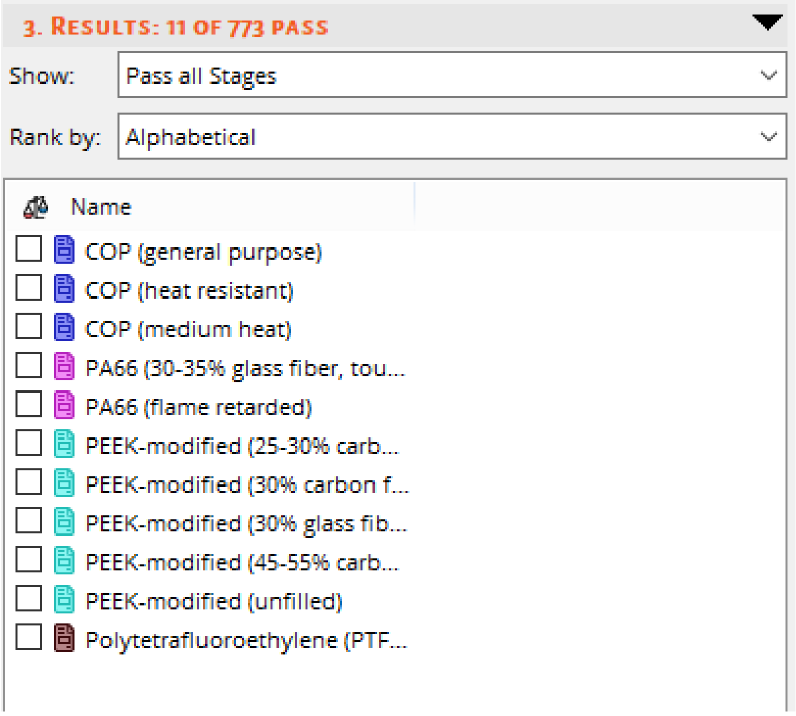


Figure 4.17: Relative comparison for all materials while highlighting the plastic materials’ subgroup

After applying the screening values (the ranges of these values are confidential and therefore not included in the report), the pool of materials was narrowed and finally around a dozen materials passed the filter as shown in Figure 4.18.



3. RESULTS: 11 OF 773 PASS

Show: Pass all Stages

Rank by: Alphabetical

Name

- ☐ COP (general purpose)
- ☐ COP (heat resistant)
- ☐ COP (medium heat)
- ☐ PA66 (30-35% glass fiber, tou...
- ☐ PA66 (flame retarded)
- ☐ PEEK-modified (25-30% carb...
- ☐ PEEK-modified (30% carbon f...
- ☐ PEEK-modified (30% glass fib...
- ☐ PEEK-modified (45-55% carb...
- ☐ PEEK-modified (unfilled)
- ☐ Polytetrafluoroethylene (PTF...

Figure 4.18: Materials that passed the required criteria

In accordance with common materials in the automotive industry, composite materials with glass or carbon fibres demonstrated strong performance in conjunction with plastics. The next step in the screening process analyses the relative cost efficiency between these materials.

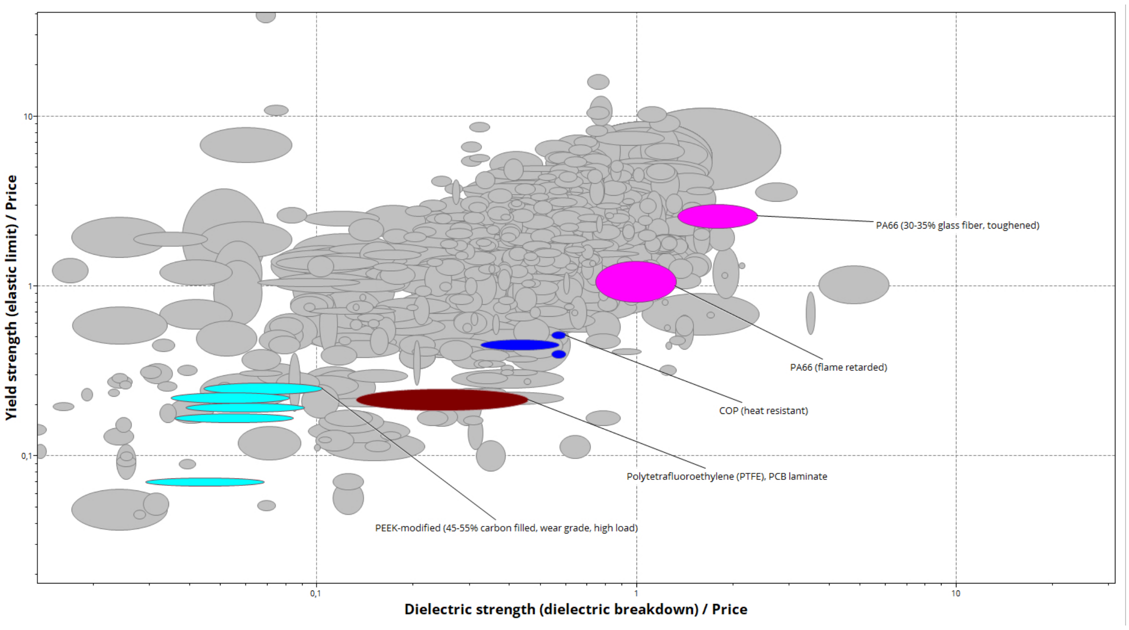


Figure 4.19: Top materials after screening

From this screening, the best performing material per price is *toughened 30% glass* *fibre-infused Polyamide 66.* This knowledge, together with previous material investigation and benchmarking information, could provide a base for an initial material choice and testing, if it were to perform too weak or strong, other materials in the list could be tested and compared.

To better understand the actual performance of the materials, Figure 4.20 shows the performance of the materials without considering prices. As the description suggests, the performance of the materials does not include their cost-effectiveness; therefore, the graphs alone do not provide sufficient information to make a decision. Including both Figures 4.20 and 4.21 simplified the comparison in performance and cost.

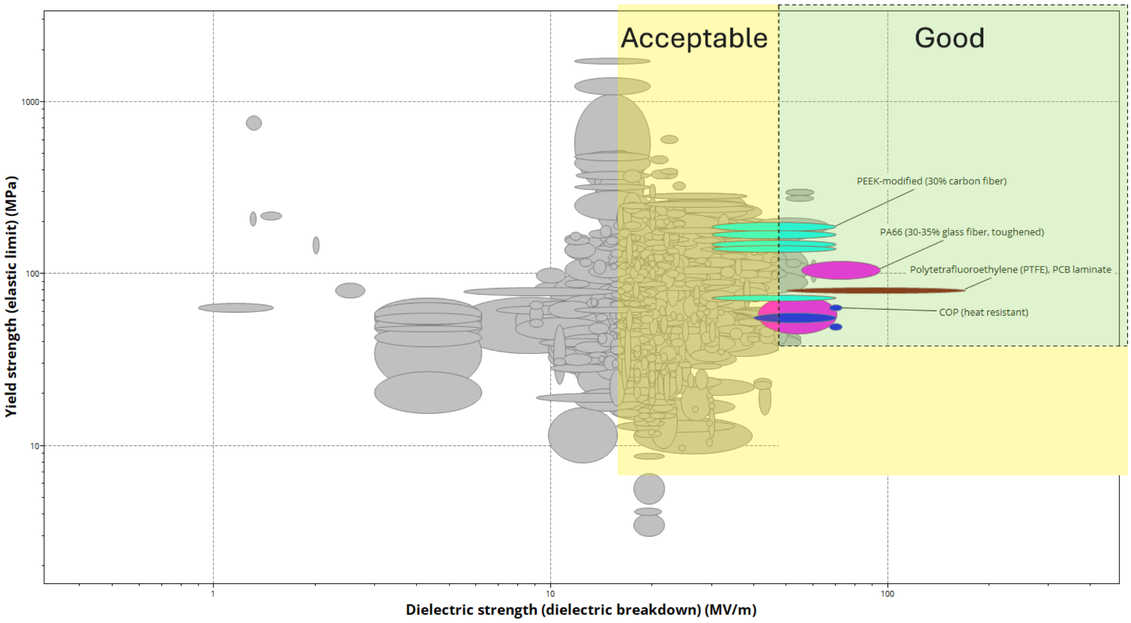


Figure 4.20: Material search for insulation material comparing dielectric strength and yield strength. Tool credit: (“Ansys Granta EduPack”, 2025).

The passed materials themselves are performance materials; however, to make the final recommendations of this project viable and implementable for large-scale production and a profitable business, the cost aspect is fundamental for tactical decisions. In summary, the last screening step provides a ”feasibility” aspect on the implementation perspective of the material with respect to the production volumes of the company relative to its industry.

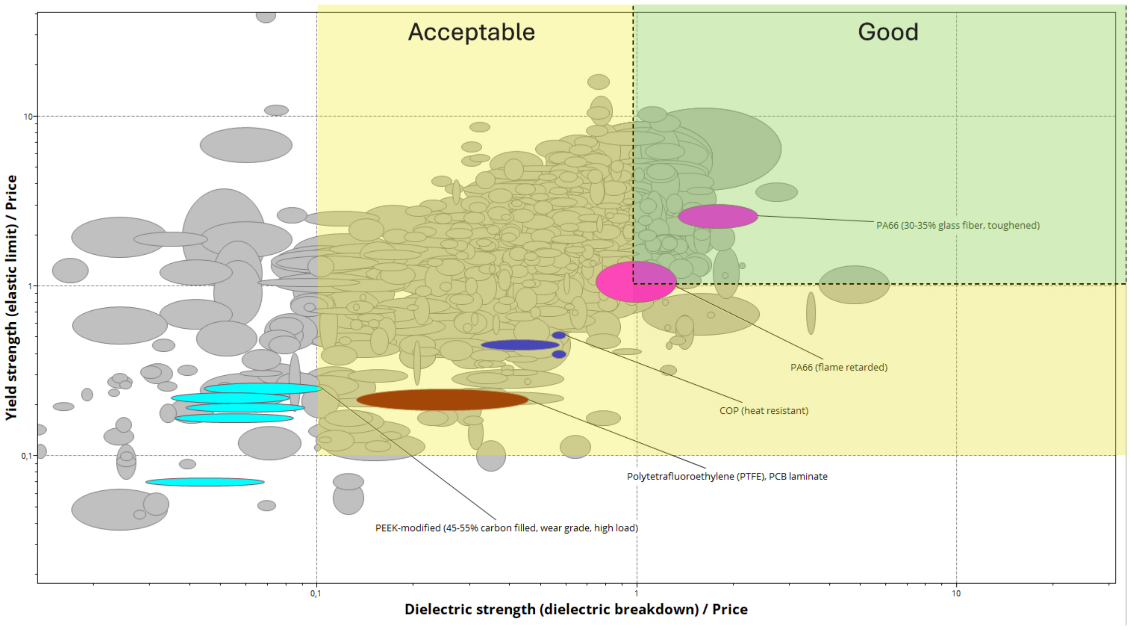


Figure 4.21: Visualisation of Figure 4.19 cost-effective performing materials. The labels are for visualisation and not for true reference of what the project considers.

4.7.3.2 Material Search in Granta Edupack (Clamping Material)

Following the selection of the insulating material, the focus shifted to identifying a suitable clamping material within the same material selection program. At this stage, the primary consideration was the material's yield strength in relation to its cost. Since electrical insulation requirements had already been addressed in the previous section, the emphasis here was placed on identifying a material with high mechanical strength that could retain its properties over an extended period under constant loading conditions, exhibiting minimal creep, particularly in comparison to polymers.

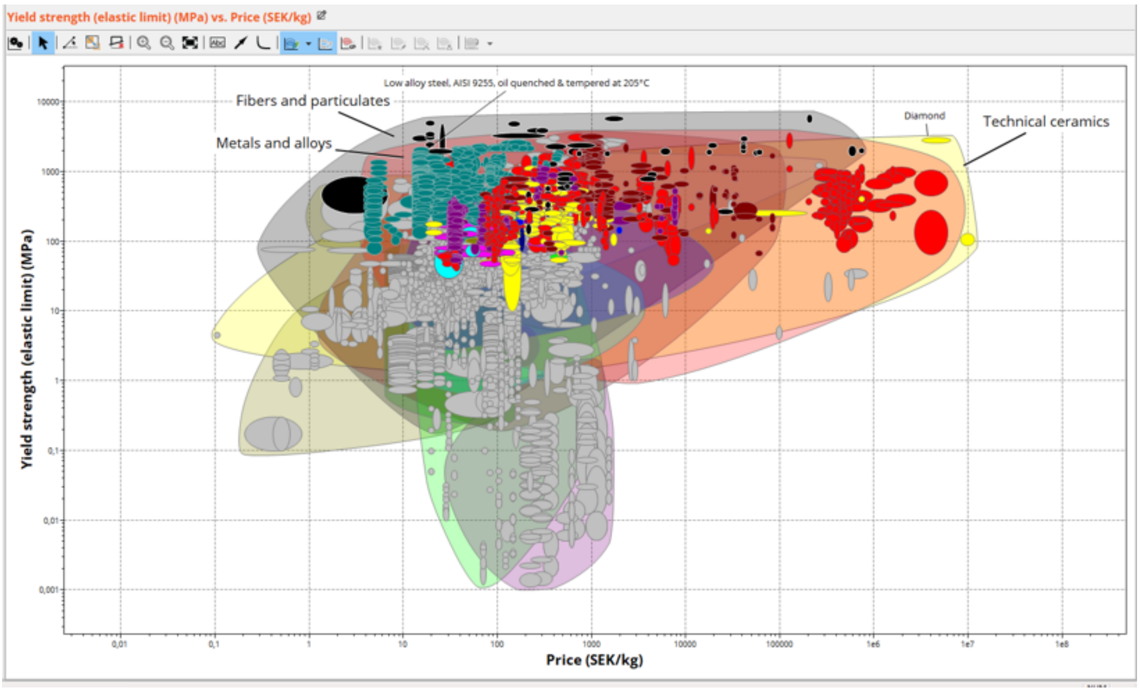


Figure 4.22: Viable material groups screened for the clamping functionality of the new design solution.

To facilitate the selection process, filters were applied to the relevant material parameters, with target value ranges set based on performance and feasibility criteria. The initial screening highlighted three viable material groups, i.e., "metals and alloys," "fibres and particulates," and "technical ceramics." However, because of the high production volumes anticipated for this application, cost-effectiveness still remained a critical factor. This consideration ultimately led to the decision to proceed with metals and alloys as the most practical option.

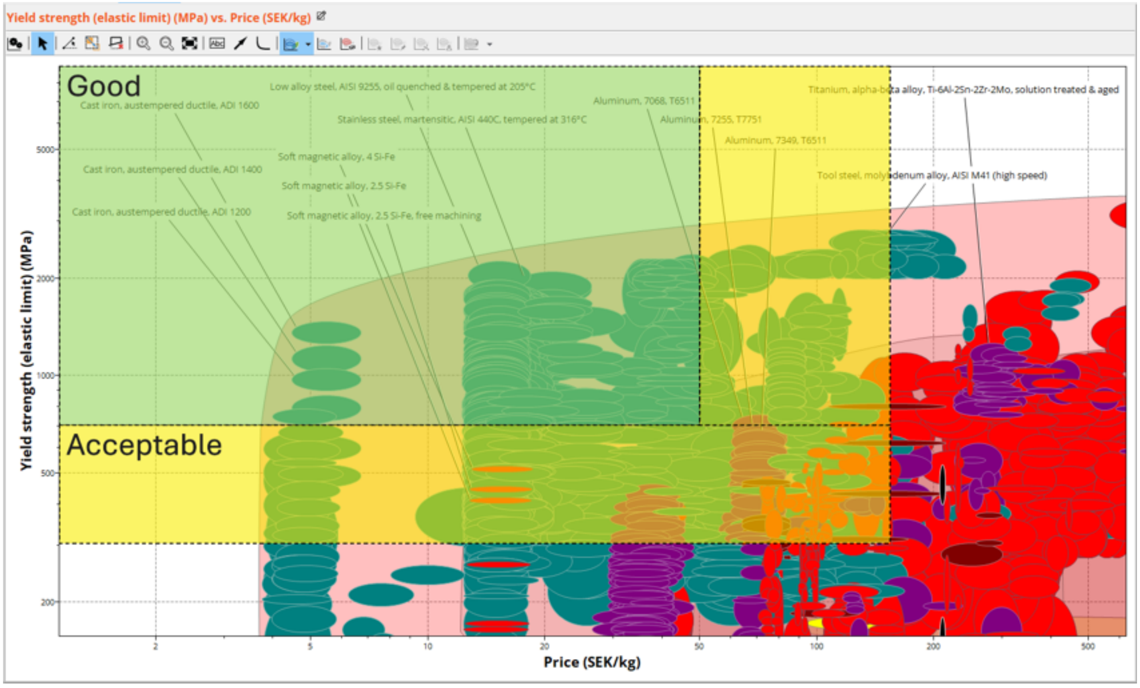


Figure 4.23: Visualisation of good and acceptable zones for the clamping material. The labels are for visualisation and not for true reference of what the project considers.

A detailed analysis was carried out, similar to that presented in Figure 4.21, was carried out to determine the acceptable and good zones for potential clamping materials, as illustrated in Figure 4.23 . From this investigation, numerous types of steel alloys, aluminium alloys and cast iron emerged as the most feasible candidates. These materials are standard and widely used in the automotive industry, which not only supports their technical suitability but also ensures their manufacturing feasibility with high-volume machining processes, further reinforcing their selection for this application.

4.7.4 ISO Standards for Testing Solution

For testing and evaluating concepts generated from the morphological matrix and concept merging in the project, the authors decided to use the Swedish ISO standard for Environmental conditions and testing of electrical equipment, 16750-3:2023 and 16750-4:2023 (Swedish-Institute-for-Standards, 2023).

ISO standard 16750-3 (Swedish-Institute-for-Standards, 2023) provides environmental and mechanical load testing parameters for electrical components in road vehicles. From the standard, the relevant parameters (testing values) are retrieved and used for the component testing requirements. For different non-disclosed reasons, some values might be modified. Values retrieved from standard:

Parameter	Value	Duration	Iterations
Shock:	Direction X, Y, Z: 500 $[m/s^2]$	6 ms	10
Vibration:	Direction X, Y: 26.8, Z: 37.2 $[m/s^2]$	48 h	10
Thermal:	Cycles range: -40 - 85 $[^oC]$	48 h	10

Table 4.4: ISO 16750 commercial vehicle testing requirements, (Swedish-Institute-for-Standards, 2023).

The values provided in Table 4.4 are used as a basis to indicate the values for the derivation of the strength analysis and later the testing requirements.

4.7.5 Use-case Assumptions

The authors set an internal goal of making the solution versatile and robust to future changes in the current area of use and for different areas of *Volvo Group*, e.g., construction equipment. Therefore, it was decided that the use case for calculating the load requirements of the concepts should adhere to a busbar with a weight of 3 kg. This originates from the TVPDC's heaviest busbar in combination with a safety margin to prepare for scenarios where the busbars are heavier, or where the number of fixation points per busbar is constrained and, therefore, is forced to be lower than optimal.

Further, the authors assumed the scenario to use two fixation points for the busbar, which translates to the minimum number of fixation points where the busbar is locked in rotation, i.e. the case where the fixation point loads are the greatest while the busbar is also locked in rotation.

As stated in Section 4.7.4: The values might be changed for specific purposes to meet internal Volvo standards or requirements set by the project team. For confidentiality reasons, these margins and elaborated values cannot be disclosed.

From the testing requirements, the shock acceleration was observed to be marginally greater than the vibration acceleration. From this, the authors understood that the shock test would affect the solution *strength* while the vibration test would screen out, or put requirements on the solution *type* of clamp force that was used including fatigue life of the solution. This gave an initial insight into what would be of importance in the technical requirements.

Item	Assumption
Busbar weight	3 $[kg]$
Number of fixation points	2 [#]

Table 4.5: Compiled table of items with assumed values.

4.7.6 Derivation of requirements

This section will derive and calculate the requirements that concepts have to endure during the testing of ISO standards for the commercial vehicle industry and their requirements for electrical components.

Ultimate loads: Starting with the shock test from Table 4.4. To calculate the maximum force experienced by the solution, *Newton's second law*, $F = ma$, is used in combination with (Swedish-Institute-for-Standards, 2023) testing acceleration (500 m/s^2) and knowledge of the assumed maximum weight of the busbar and the minimum fixation points used.

$$F_{max_{solution}} = \frac{m_{busbar_{max}}}{N_{min_{fixations}}} * a[N] \tag{4.1}$$

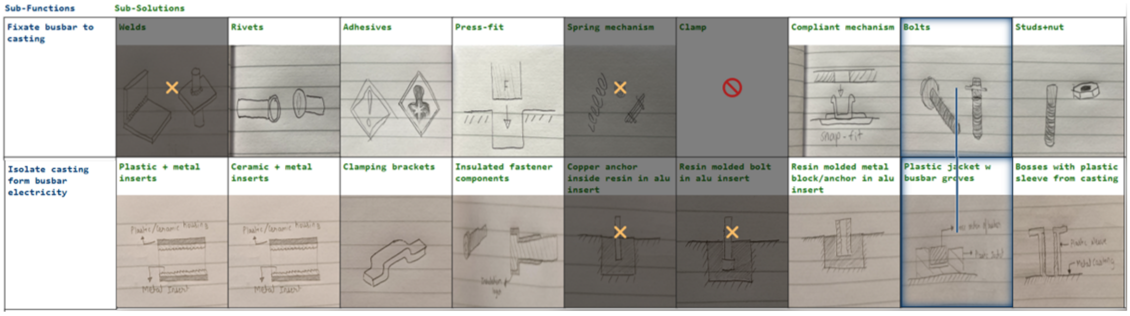
Inserting values,

$$F_{max_{solution}} = \frac{3}{2} * 500 = 1.5 * 500 = 750[N] \tag{4.2}$$

4.8 Concept Combination Table

The knowledge gathered from sections 4.4 and 4.5 was used to generate a *Concept combination table/Morphological matrix* with the help of the tool ("Morpheus", 2025). For both the sub-functions of isolating the busbar from the casting and clamping the busbar through a suitable means, nine sub-solutions for each were finalised. Rough sketches were drawn individually for each sub-solution and imported into the tool.

This resulted in 81 unconstrained concepts because it being a 9 x 9 matrix. However, some concepts were delimited owing to the feasibility and compatibility of each sub-solution bringing down the pool of concepts to 47. The infeasibility or incompatibility of the rejected concepts was based on their functions; for example, it might not be feasible to make a rivet out of plastic or ceramic. One of the combination of the tool is shown in Figure 4.24. For this concept, the tool combined the sub-solutions of using bolts with a plastic jacket, akin to the *E-Actros'* PDU in section 4.6. It also depicts the unfeasible options such as the plastic jacket cannot be welded to the casting due to the usage of different materials.



Sub-Functions	Sub-Solutions								
Fixate busbar to casting	Welds	Rivets	Adhesives	Press-fit	Spring mechanism	Clamp	Compliant mechanism	Bolts	Studs+nut
Isolate casting form busbar electricity	Plastic + metal inserts	Ceramic + metal inserts	Clamping brackets	Insulated fastener components	Copper anchor inside resin in alu insert	Resin molded bolt in alu insert	Resin molded metal block/anchor in alu insert	Plastic jacket w busbar grooves	Bosses with plastic sleeve from casting

Figure 4.24: One of the iterations from Morpheus tool

4.8.1 Brainstorming Sessions

As complementary work to the *Concept combination table* with the main objective of combining and understanding how functions of concepts can be combined and cross-bred into new concepts, through total *suspended judgement* (Ulrich et al., 2011a, c.7, p.132). This was achieved in multiple sessions where engineers from different *TVSD* areas were invited, and together with the project team discussed the benefits and consequences of the different concepts generated. These sessions aided in yielding some rough concept sketches as shown in Figure 4.25

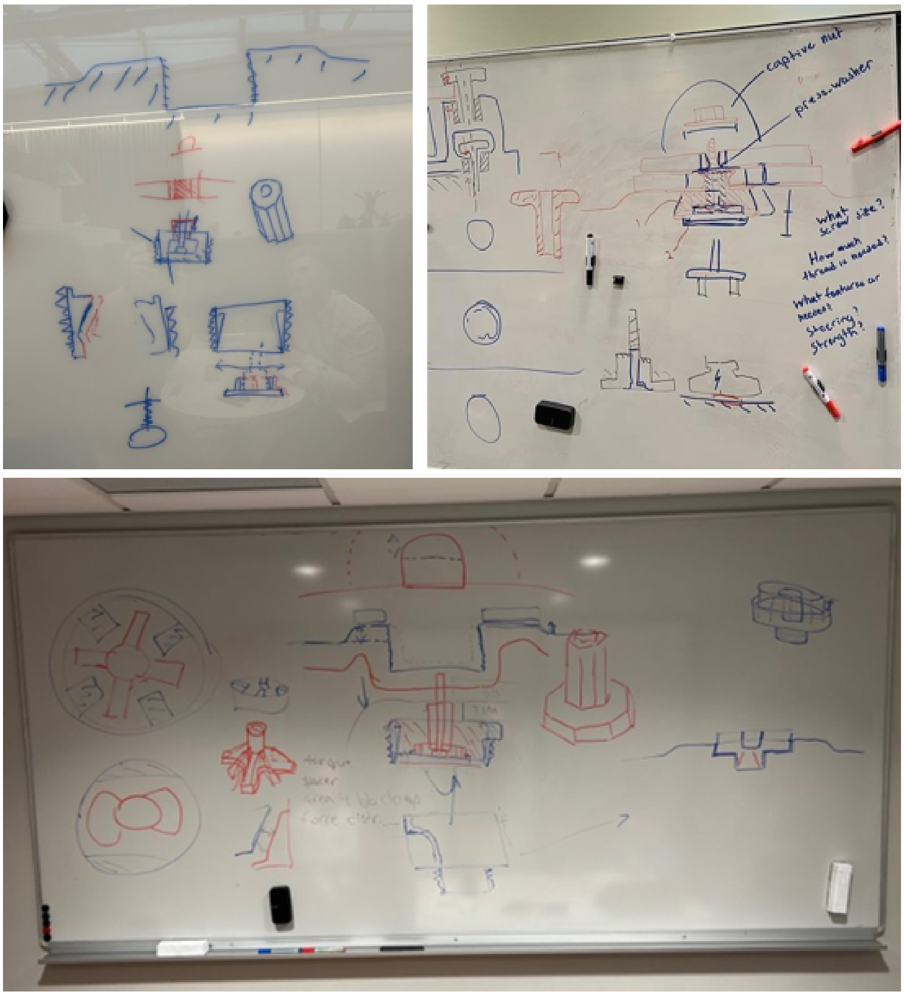


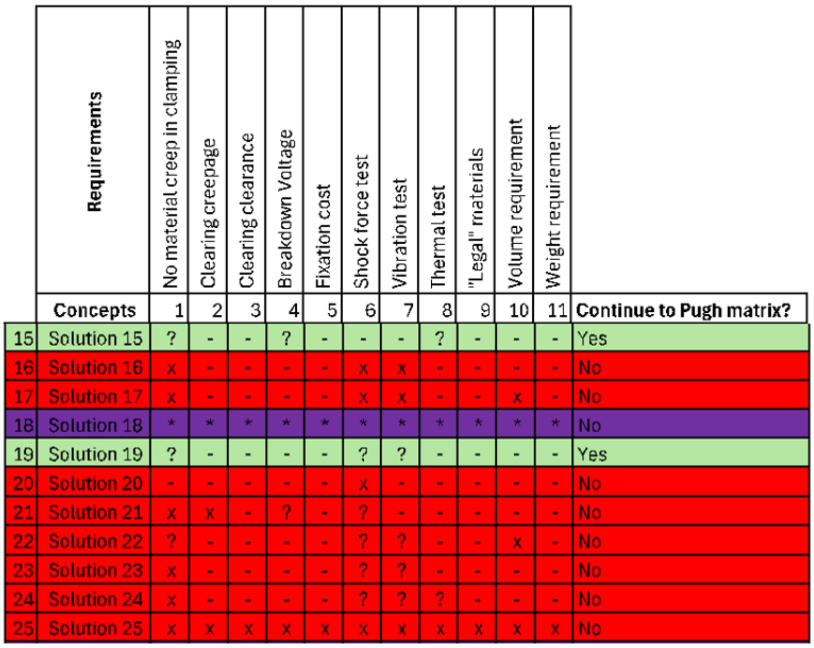
Figure 4.25: Brainstorming concept sketches

This widened the team's insight into how the solution could be implemented in the current product, but also common pitfalls and valuable experiences from working engineers. This generated a dimension of reality and feasibility for the newly combined concepts. They became the result of a clean sheet in the form of the creative and unbiased project team and the insight and understanding of the product and reality of engineering from the working engineers.
The main focus on the discussion became DFA and DFM as the authors had multiple concepts which required more certainty in realisability of manufacturing sub-

components or how it should or could be assembled by the production facility. After each session, the project team iterated and further defined the new ideas gained from the session. This process proved successful, as the new concepts provided new ideas and insights to the working engineers. In addition, the iterative process after the brainstorming sessions became a good way to reflect on the solutions and the process.

4.9 Elimination Matrix

Based on the required criteria, concepts that did not pass one or more of them were screened from the concept selection process. There were a total of 11 criteria involved which are shown in the example Figure 4.26. The elimination criteria were (-) ”pass”, (x) ”fail”, (*) ”partial elimination due to alternatives”, or (?) ”need more information”. The concept row was marked green if the concept was continued to the *Pugh matrix*, red if the concept was screened out, and purple if the concept was eliminated/merged with another concept that was similar but proved to be better. The majority of concepts were terminated in this process. The reasons are discussed below.



	Requirements	No material creep in clamping	Clearing creepage	Clearing clearance	Breakdown Voltage	Fixation cost	Shock force test	Vibration test	Thermal test	"Legal" materials	Volume requirement	Weight requirement	
	Concepts	1	2	3	4	5	6	7	8	9	10	11	**Continue to Pugh matrix?**
15	Solution 15	?	-	-	?	-	-	-	?	-	-	-	Yes
16	Solution 16	x	-	-	-	-	x	x	-	-	-	-	No
17	Solution 17	x	-	-	-	-	x	x	-	-	x	-	No
18	Solution 18	*	*	*	*	*	*	*	*	*	*	*	No
19	Solution 19	?	-	-	-	-	?	?	-	-	-	-	Yes
20	Solution 20	-	-	-	-	-	x	-	-	-	-	-	No
21	Solution 21	x	x	-	?	-	?	-	-	-	-	-	No
22	Solution 22	?	-	-	-	-	?	?	-	-	x	-	No
23	Solution 23	x	-	-	-	-	?	?	-	-	-	-	No
24	Solution 24	x	-	-	-	-	?	?	?	-	-	-	No
25	Solution 25	x	x	x	x	x	x	x	x	x	x	x	No

Figure 4.26: Example of 10 concepts from the Elimination matrix

Concepts that relied on plastic material to provide the clamping force to the busbar were eliminated. The reason being is that plastic will not perform well if loaded with a constant clamping force over time and tends to creep, as proved by the current concept. The authors thought that the solution should have a clamping medium with robust metal-to-metal connection and should not have *too* concept attributes similar to the current solution.

Concepts implying a risk of leaving conductive residue or shrapnel inside the box - and, thereby, the risk of short circuiting from electricity travelling via the particles - were eliminated because of this risk. This risk eliminated concepts using rivets. Concepts relying on thin plastics with high mechanical stress concentration were also terminated because of the risk of weakened electromechanical strength over time.

The concepts of having insulated fastener components or over-moulded components were also screened because they would rely on a thin layer of insulation given the desired volume. The thin layer of insulation might be a safety hazard, as it has a comparatively lower breakdown voltage and is more prone to electromechanical breakdown. Subsections 2.2.2.2 and 2.2.4 indicate that with a reduction in the thickness of the insulator, the breakdown voltage of that material decreases, and this is also further worsened by higher voltage stresses.

The shock force will affect solutions that have a press fit as their source of clamping force. This could be dangerous due to loosening, misalignment, and material degradation due to the shock force. Furthermore, plastic-compliant mechanisms can also break due to increased stress concentration in critical places.

Similarly to the shock force test, the vibration test also screens concepts with press fits and compliant mechanisms. High-frequency vibrations could cause micro-slippage in the press fits and permanent deformation of compliant mechanisms. Hence, they were screened to avoid any potential risks and consequences of using these.

Volvo, and thereby, the authors, work to phase out harmful chemicals that would affect sustainability goals. Stronger adhesives, i.e. adhesives required for fixation of busbars are not disassemblable and therefore complicate the maintenance- and assembly processes. In addition, they are commonly toxic and require curing time. The mentioned reasons justified screening of the adhesives fixation alternative.

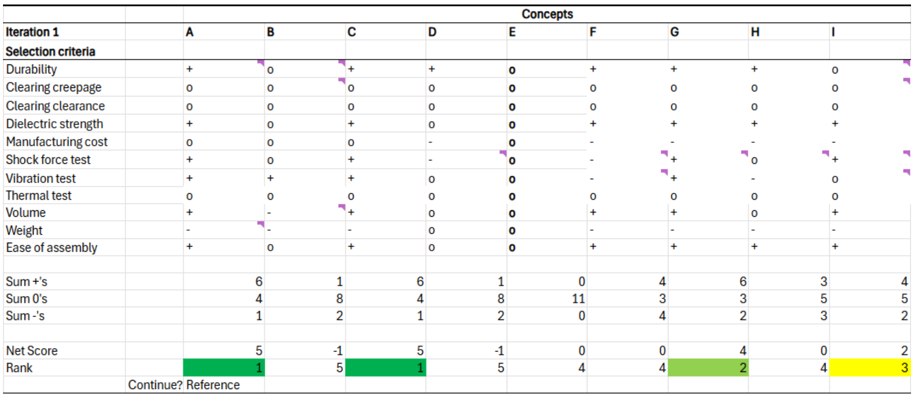
The packaging design of the components restricts the use of concepts marginally larger than the current fixation method. Therefore, concepts using plastic plates and large covers with grooves for the busbars were terminated. The plastic cover could be investigated in a future concept of the TVPDC.

After comparing the relative estimated weights, concepts with plastic jackets and grooves similar to the concepts in Section 4.6 were screened, as they seemed to be much heavier than their counterparts. Although volume appeared to be important in this case, weight also felt quite infeasible.

Comments are regarded as sensitive information and, therefore, are redacted. For a complete table, see Appendix F.

4.10 Pugh Matrix

The elimination matrix was iterated and the concepts were reviewed three times. Of 47 concepts, nine concepts were continued to the *Pugh Screening matrix.* The authors aimed at iterating the matrix three to five times depending on the convergence of the concept ranks based on different references. This resulted in three iterations in which the top four concepts ranked similarly in all three iterations. We can further discuss in general why some concepts were ranked lower than the other.



		Concepts								
Iteration 1		**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Selection criteria										
Durability		+	o	+	+	**o**	+	+	+	o
Clearing creepage		o	o	o	o	**o**	o	o	o	o
Clearing clearance		o	o	o	o	**o**	o	o	o	o
Dielectric strength		+	o	+	o	**o**	+	+	+	+
Manufacturing cost		o	o	o	-	**o**	-	-	-	-
Shock force test		+	o	+	-	**o**	-	+	o	+
Vibration test		+	+	+	o	**o**	-	+	-	o
Thermal test		o	o	o	o	**o**	o	o	o	o
Volume		+	-	+	o	**o**	+	+	o	+
Weight		-	-	-	o	**o**	-	-	-	-
Ease of assembly		+	o	+	o	**o**	+	+	+	+
Sum +'s		6	1	6	1	0	4	6	3	4
Sum 0's		4	8	4	8	11	3	3	5	5
Sum -'s		1	2	1	2	0	4	2	3	2
Net Score		5	-1	5	-1	0	0	4	0	2
Rank		1	5	1	5	4	4	2	4	3
	Continue?	Reference								

Figure 4.27: Iteration 1 of the *Pugh screening matrix.*

Design concepts with materials such as plastic or ceramics bearing the same clamping load as their metal counterparts, i.e., concepts B, D, and E were rendered inferior. Given that plastics exhibit more creep over time as a result of their chemical composition and structure, other concepts were ranked higher.

The project team found potential in the concept A, C, G, and I's ability to adapt the insulation thickness after demand while not affecting the volume above the busbar which were observed as a strength. Furthermore, increasing the value of breakdown voltage with a thicker insulating material proved as a plus point, therefore, they received a superior score in this criteria relative to the rest.

For the manufacturing cost, the team assumed outsourcing the production to a supplier. The cost estimations were based on the complexities of the geometries, standard parts or custom parts, production methods, materials, post processing & treatment required for tolerances, number of steps, tools, machines and time to finishing the part.

The shock force criterion was, like the material creep, dependent on which material clamped the busbars for the concepts if a weaker material like plastic is the isolated clamp provider for the busbar, this rendered a lower score relative to concepts where the clamp is only metal.

Evaluation of vibration capacity rendered rigid standard fastener components (i.e. bolts, nuts, welds) and concepts clamping the busbar directly with durable material (metal) to higher score than concepts relying on weaker materials that relax or degrade over time.

Thermal cycling evaluation proved infeasible judging by drawings and intuition. However, all concepts that use similar or the same type of industrial-grade plastics with similar dimensions except concept D that uses ceramic. This could give an indication that the performance would output a binary result if the concept completed the test or not, rather than a gradient of eventual performance advantages or disadvantages for each concept.

The relative volume occupancy of each concept was compared and assessed. However, few concepts appeared to have more volume occupancy in terms of height, width, and depth; this could cause some limitations to the packaging and would not be ideal, even if plans were underway to downsize the box in the future.

The weight criteria considered the weight of the concept. Relatively, some concepts were heavier compared to each other; however, the volumes they occupied in the system were different.

For this assembly criterion, the number of parts, steps, and number of tools involved and the risk of re-assembly due to positioning error were evaluated for all concepts. Concepts A, C, G, and I again proved to be better compared to their counterparts due to having smaller number of parts and lesser number of steps, increasing the efficiency and decreasing the assembly time.

4.11 Concept Selection

The task of this Master's thesis was to ”investigate new busbar fixation concepts” for *Volvo*. The authors decided to use a set-based approach (set-based concurrent engineering, Section 3.8.1), thus keeping as many options available as possible for as late decisions as possible.

As stated in Section 4.10, the *Pugh screening matrix* resulted in four concepts, two of which were merged after consideration, resulting in three final concepts. During a concept gate in the form of a midterm presentation held in *Volvo CampX* on April 16th, 2025, the process and concepts along with their relative benefits and disadvantages were presented for the TVSD department. This was done to generate feedback from within the team and the interviewees used at the beginning of the project, given that they had the knowledge to decide and how the final concepts could be implemented.

The presentation ended with a Questions & Answers-forum where the working engineers raised perceived caveats or misunderstandings. The continued internal discussions throughout the day provided constructive feedback and suggestions for improvements in the design comprising concept engineers visualising an option of cheaper production and more efficient assembly of the concept.

In addition, a second updated midterm presentation was conducted (online) for a Technical Preparation Engineer based at the operations facility (France) with the purpose of updating the project process and results, and receiving feedback on DFA and implementation feasibility for the final concepts.

Feedback shed light on a new, unknown feature in one of the assembly tools, which hindered the placement of a component if a feature in the concepts exceeded a certain value. This information rendered a problem for two of the concepts, one of which could be solved with minor effects on the final result. The second concept and problem would require a change in the use of the current tool, which would add cost. This was considered a downside, and the concept was down-prioritised until a solution had emerged.

4.12 Preliminary Concepts

Before the concept gate, the initial concepts outlined in the Pugh matrix were developed using the CAD tool *Creo Parametric* as explained in Section 3.12.1, and was further visualised using *Blender* for improved clarity in the presentation. These models were designed with approximate dimensions, although feasible dimensional ranges were established based on factors such as the volume occupied within the TVPDC, creepage, clearance, and the area required for clamping force.

All concepts shared a similar appearance, primarily due to the high-ranking approach in the *Pugh matrix*, which utilised a threaded, cylindrical, hollow metal socket as the base for the insert. This metal socket featured three different central design variations, each incorporating a shaft-like structure. The gap between the shaft and the socket was filled with resin or plastic, which served as an insulating layer to prevent electrical conduction between the two components.
Each concept offered a different interpretation of the central shaft-like structure as follows and they have been illustrated in Figure 4.28

- Concept A consists of an inverted bolt with a long nut and a captive nut for fastening.
- Concept C features a custom-made metal anchor with a threaded hole to accommodate the same bolt size for fastening.
- Concept I employs a copper stud/anchor that could be welded to the busbar to hold in place.

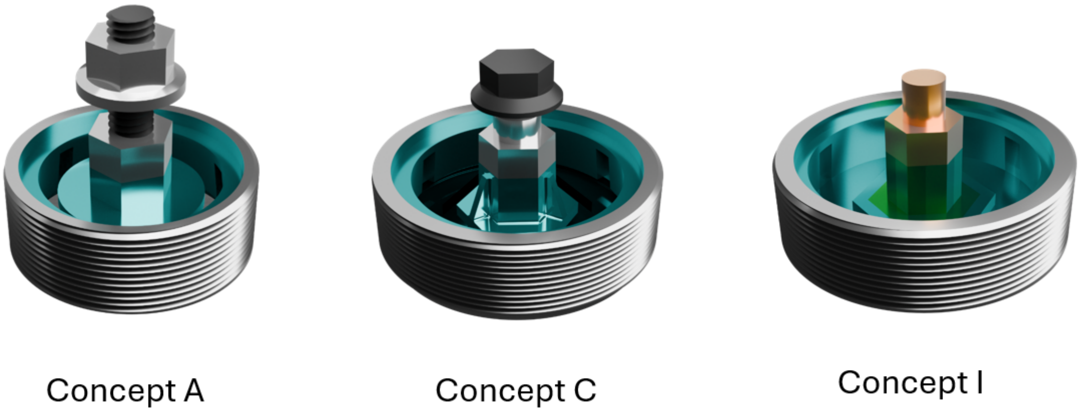
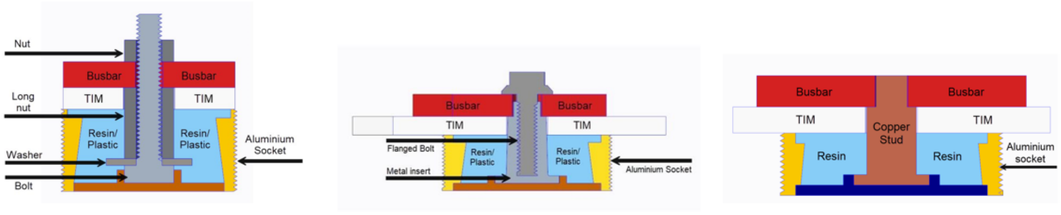

Concept A
Concept C
Concept I

Figure 4.28: Visualisation of Concepts in Blender

A distinguishing feature across all concepts was a step geometry, which improved the mechanical clamping of the busbar through direct metal contact rather than relying on an insulating layer of polymer, which can deform over time due to creep which might not be robust. Despite using different insert components, all concepts were designed to accommodate the thermal interface material (TIM) and busbar in a consistent manner. The cross section of the above concepts can be seen in Figure 4.29.



Concept A Concept C Concept I

Figure 4.29: Cross-section of all the preliminary concepts

Furthermore, the separation of clamping and electrical insulation functions emerged as a unique and effective strategy, significantly contributing to the development of more reliable solutions within the identified improvement area. Figure 4.29 display different iterations of Concepts A, C and I which can be identified through different proportionalities of the widths and depths of the socket and insulation material respectively.

4.13 Concept Gate

The concept gate presentation was carried out and, after a Q&A session, the discussion yielded feedback on the design. The recommendations comprised suggestions that the design could be *cheaper* if using less parts and would probably be strong enough without the external metal socket.

The recommendations focused on ways to make the design more cost effective. One of the main ideas was to reduce the number of parts in the assembly, which would simplify manufacturing and lower costs. During discussions, it became clear that the insert would not need to be tightened with high torque when installed in the TVPDC. This is because the friction between the busbar and the central shaft provides strong clamping.

As mentioned in Section 2.3.1, having a stiffer clamping part is very beneficial to having a reliable threaded joint. Due to this, even if the insert is not torqued down to a particular standard value, it is unlikely to rotate out of place, especially if the busbar is securely held in multiple spots. This means that the entire assembly with the busbar will be geometrically locked in place. Furthermore, the stiffness of the busbar also becomes important when subjected to a rotational forces, as it helps prevent the insert from coming out of position.

With that in mind, it was decided to move forward without the metal socket. Instead, the new concept keeps the central shaft iterations which is overmoulded with plastic in a simple cylindrical shape with external threads.

This approach not only simplifies the design, but also offers broader system-level benefits. It opens up opportunities for cost savings in other areas, such as allowing the use of more cost-effective or heat-conducting TIM materials and allowing for a more configurable busbar design. Hence, on a component level, the revised concept is estimated to perform superior to the current concept for an approximated similar cost. However, on a system level, it allows for a broader set of configurations, performance improvements and cost-savings.

4.14 Detailed Design

The detailed design phase of this project was strongly guided by the outcomes and discussions from the concept gate. The insights gained during that stage provided a clear direction and a foundation for the next steps. The authors decided to carry forward the learnings, feedback, and recommended concepts from the concept gate into detailed design work.

With a more defined path in place, the focus during this phase will be on developing accurate CAD models of the selected concept. These models will reflect the refinements discussed previously and incorporate all necessary dimensional and functional considerations. In addition to modelling, the plan also included the performing of structural analysis to evaluate the mechanical performance and reliability of the new design under expected loads and conditions. The following subsections include information and figures on the CAD and the CAE of the newly discussed concept.

4.14.1 CAD

Following the discussions and outcomes of the concept gate, a detailed 3D CAD model of the selected concept was developed to translate the idea into a fully defined design as illustrated in Figure 4.30. The modelling mainly focused on the two key components of the insert: a metal anchor and the overmoulded plastic housing.

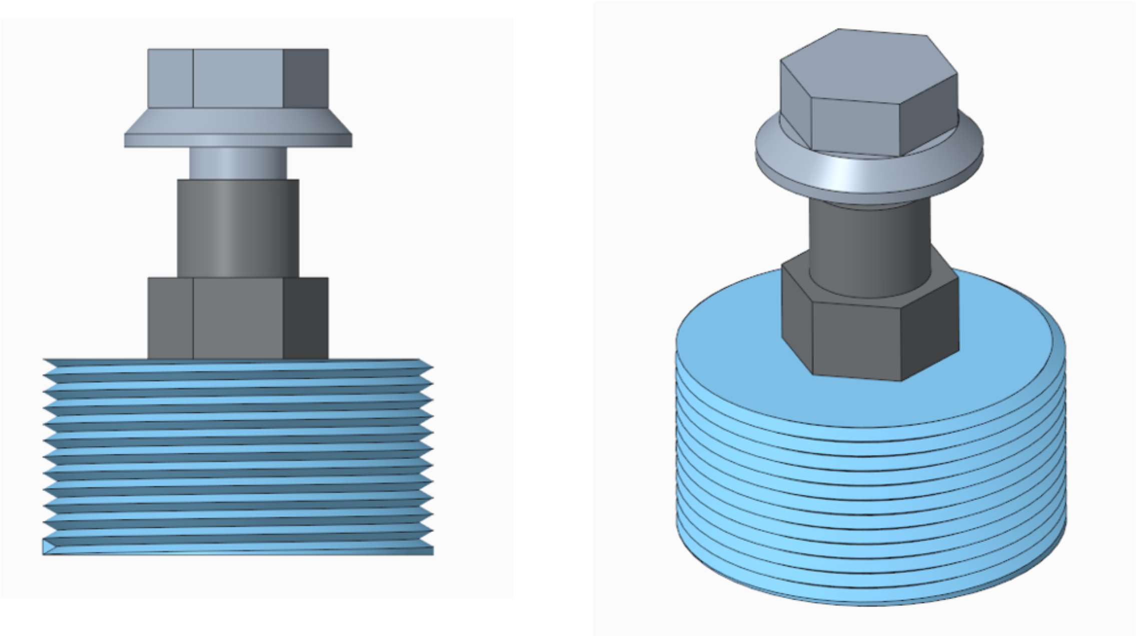


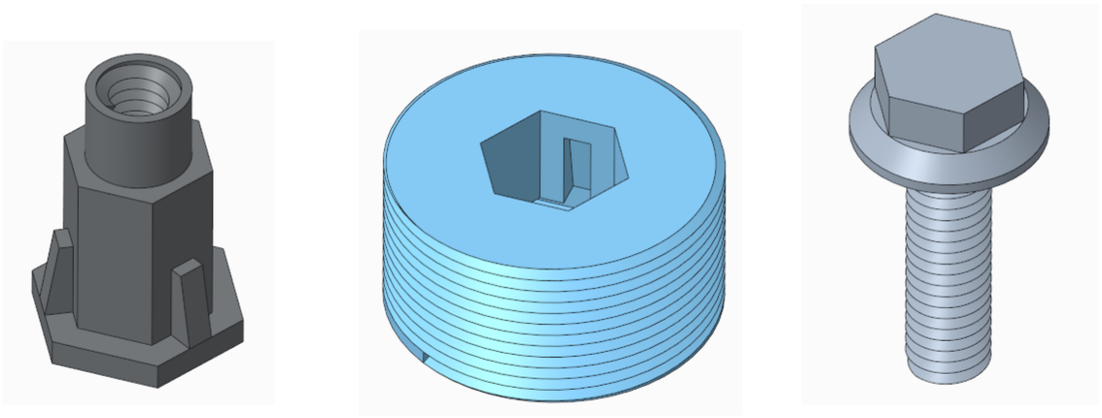
Figure 4.30: Reviewed iteration of Concept C, post concept gate discussions.

The metal anchor features a hexagonal outer profile, specifically designed to allow assembly workers to grip and torque the insert into the TVPDC using standard tools. To improve torque transmission and mechanical stability, the anchor includes three support fins/ribs with a wider base. These fins/ribs not only help distribute torque evenly during installation, but also enhance tear-out resistance by increasing the bonding surface area with the plastic overmould.

Finally, the anchor also has a very critical feature, which is ”the step”. This step is located above the hexagonal profile of the anchor with a cylindrical feature having a smaller outer diameter than the hexagonal profile. This step feature has a flat surface on which the busbar can be directly clamped without relying on the reaction forces from the TIM. This ensures that it has a robust metal-to-metal contact which can be used for preloaded joints reliably.

The plastic component was modelled as a cylindrical body that encapsulates the anchor, ensuring complete electrical insulation between the metal insert and the TVPDC. The cylinder looks wider compared to the anchor due to creepage requirements. External threads were added to the outer surface of the plastic part, allowing it to securely engage the threaded cavity of the TVPDC casting.

To better simulate the real assembly environment, additional parts such as a dummy TIM, a busbar, and a flanged screw were also modelled. These components help to visualise the complete assembly and validate fit and clearances. Manufacturability was also taken into account throughout the modelling process. Potential mould release directions and undercuts were also reviewed to confirm feasibility for production tooling. The CAD model captures both the mechanical and functional intent of the new insert concept and serves as the foundation for further structural analysis and prototyping. The visualisation of the final concept is shown in Figure 4.30 and the separated parts are shown in Figure 4.31.



Metal Anchor

Plastic Cylinder

Flange Bolt

Figure 4.31: Disassembled parts of the final iteration

4.14.2 CAE (Static Structural Analysis)

To evaluate and analyse the mechanical performance of the insert, a static structural analysis was performed using ANSYS Mechanical. The failure modes outlined in Section 2.4 were of particular relevance, as they directly relate to the structural integrity of the insert under operational loading conditions. These modes guided the definition of boundary conditions and the interpretation of results.

Two types of static structural simulations were performed to evaluate the mechanical performance of the assembly: tear-out strength and shear strength. These simulations were conducted for two different anchor materials which are structural steel and aluminium. They have been detailed as follows with only the aluminium anchor's context. The results for the steel anchor can be found in Appendix K and J.

4.14.2.1 Tear-out Strength

This simulation was conducted to assess the potential for the insert or its components to be torn out of the housing. The purpose was to understand how the insert, along with the busbar and TIM, would behave when the bolt experiences an axial load. The applied boundary conditions are listed below and illustrated in Figure 4.32.

- A fixed support applied to the threaded surface of the plastic insert,representing its engagement with the TVPDC casting.
- Preload on the bolt that clamps the busbar in place.
- An axial force was applied to the bolt, with the magnitude based on the highest load calculated in Subsection 4.7.6.

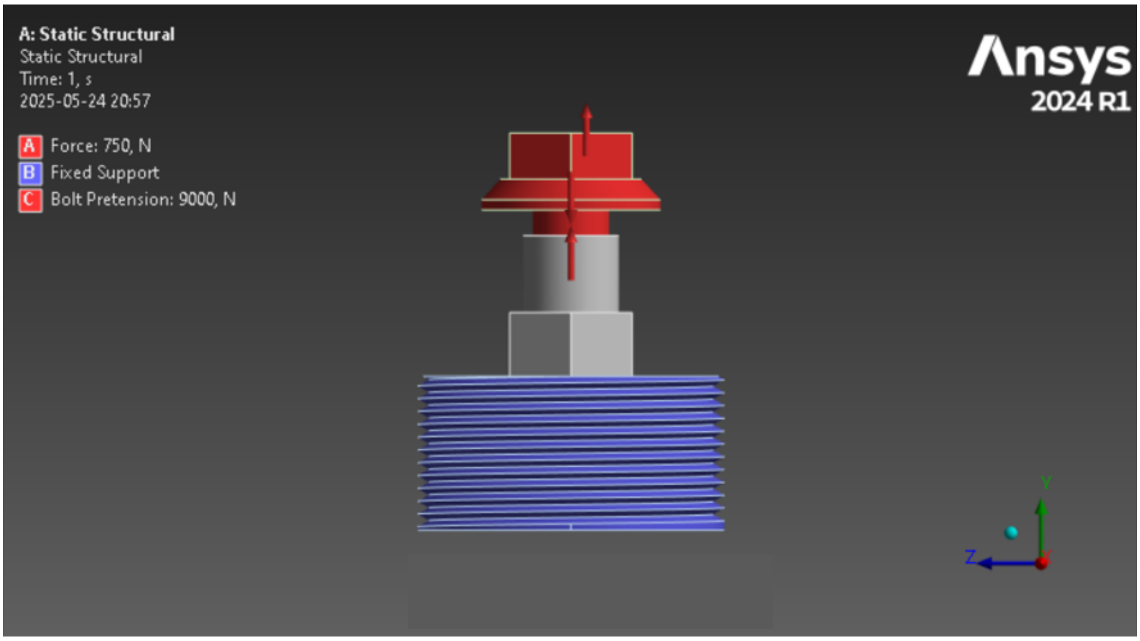


Figure 4.32: Boundary condition for the insert for tear-out strength test

Each component in the assembly was assigned appropriate material properties based on the insights of external research and the findings presented in Section 4.7.3.

The contact interactions between the components were carefully defined. Most interfaces, such as those between the busbar and the anchor, anchor and bolt, and the plastic and anchor were set as rough contacts instead of bonded to accurately model frictional resistance and prevent unrealistic behaviour.

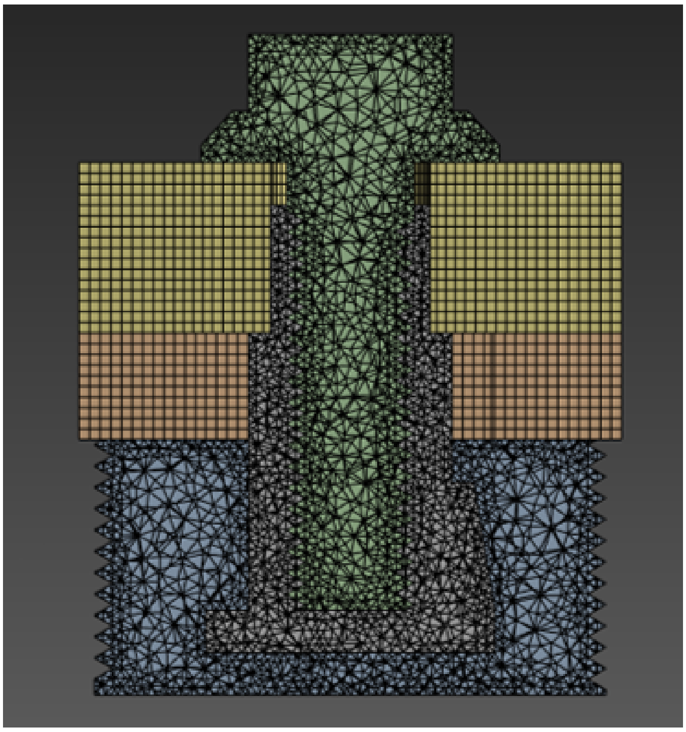


Figure 4.33: Meshed assembly

Figure 4.33 shows the finely meshed model of the assembly. The analysis focused on two key results: stress and deformation. These provide knowledge on the mechanical response of the insert under load and help assess safety margins in relation to the yield strengths of the respective materials. An exaggerated deformation view is shown in Figure 4.34, where the anchor appears to be "pulled out" from the overmoulded plastic, and the bolt preload is visibly compressing the busbar.

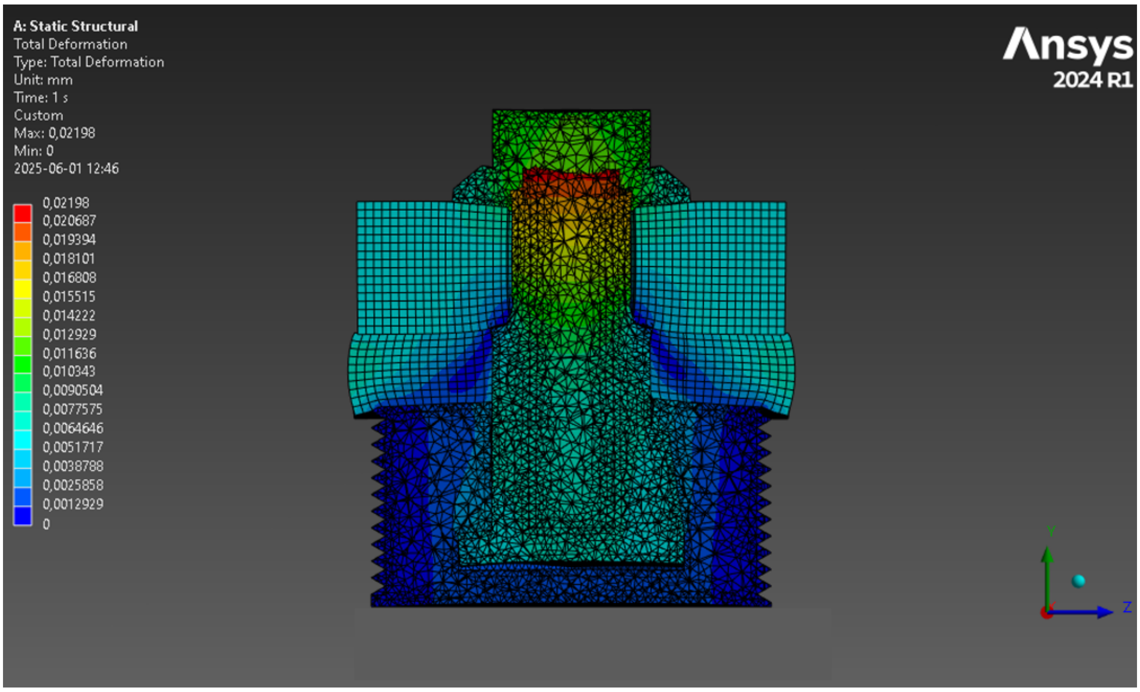


Figure 4.34: Auto-scale (34x) deformation of the assembly for tear-out strength test

From the results, it was observed that the deformation was minimal and occurred mainly around the bolt shank area due to the stretching of the bolt under pretension. The stress concentrations were also located primarily around the bolt shank and the clamping area of the busbar due to compression, as shown in Figure 4.35. The maximum stress observed at a singularity point in the bolt was 405 MPa, well below the bolt's yield strength of 640 MPa, indicating that the design is safe under these loading conditions.

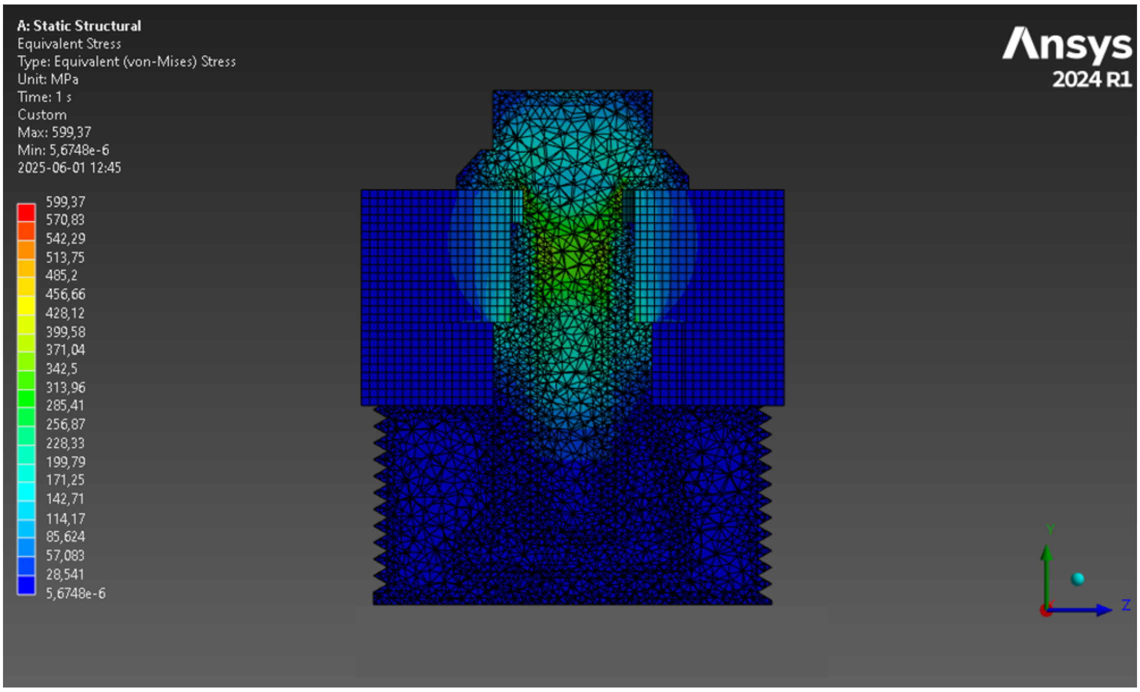


Figure 4.35: Equivalent stress (Von-Mises) of the assembly for tear-out strength test

These results align with findings from (Ansys Innovation Space, 2022), supporting the validity of the simulation. Some stress spikes observed are attributed to mesh singularities and limitations of the student version of the software, and can be reasonably disregarded. This singularity is illustrated in Figure 4.36

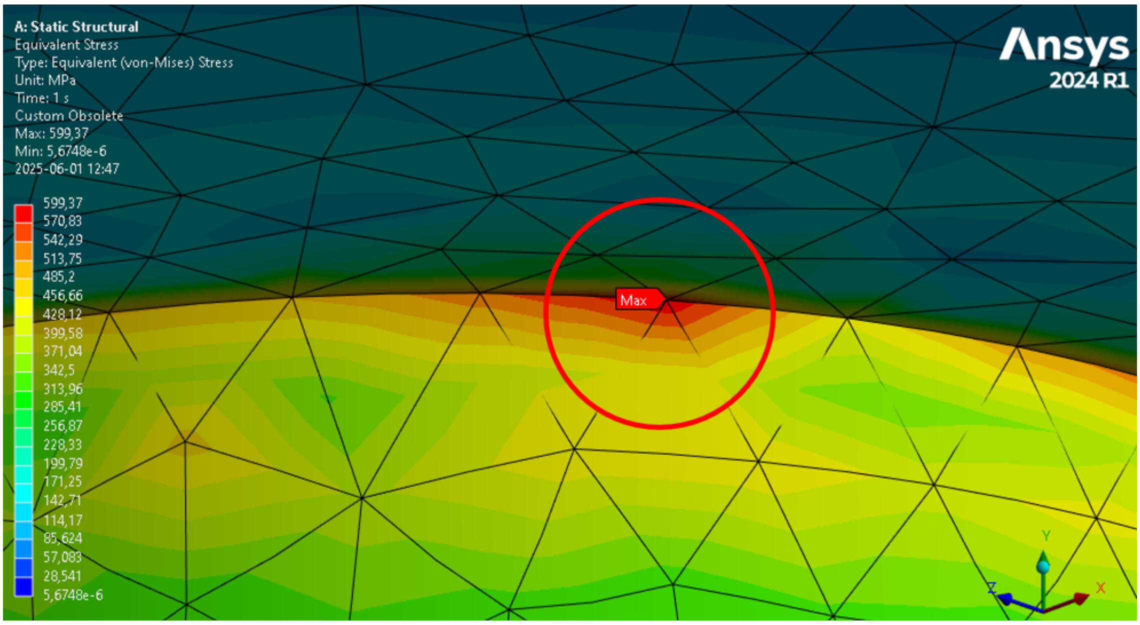


Figure 4.36: Maximum stress at singularity near bolt neck

4.14.2.2 Shear Strength

This simulation aimed to evaluate the shear strength of the anchor where the busbar is mounted. Using the same ultimate load value as before (750 N), it was initially recognised that the preload in the clamped condition would resist this load through friction alone. Therefore, applying this load directly in the same boundary setting would not produce realistic results. However, to assess the strength of the anchor itself under worst-case conditions, the simulation was carried out under the assumption that preload is lost.

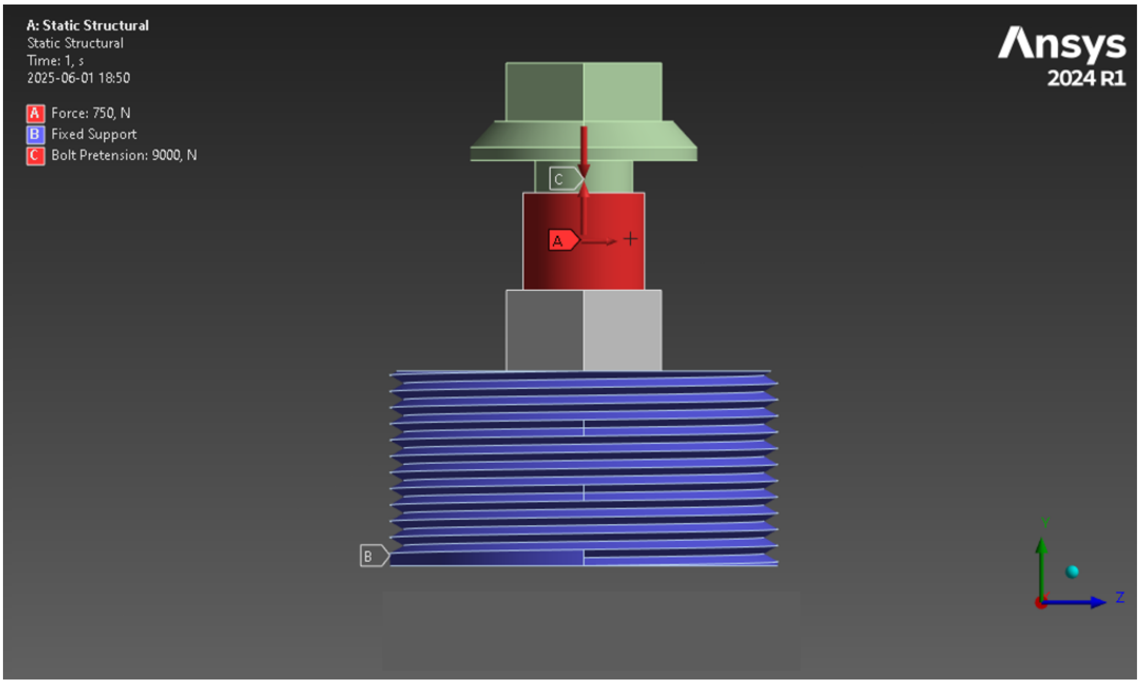


Figure 4.37: Boundary condition for the insert for shear strength test

The boundary conditions remained the same, with the only change being the orientation and position of the external load, now applied in the shear direction, as shown in Figure 4.37. The materials, contact definitions, and mesh parameters were kept identical to those used in the tear-out strength simulation. The results of exaggerated deformation and stress are shown in Figures 4.38 and 4.39, respectively.

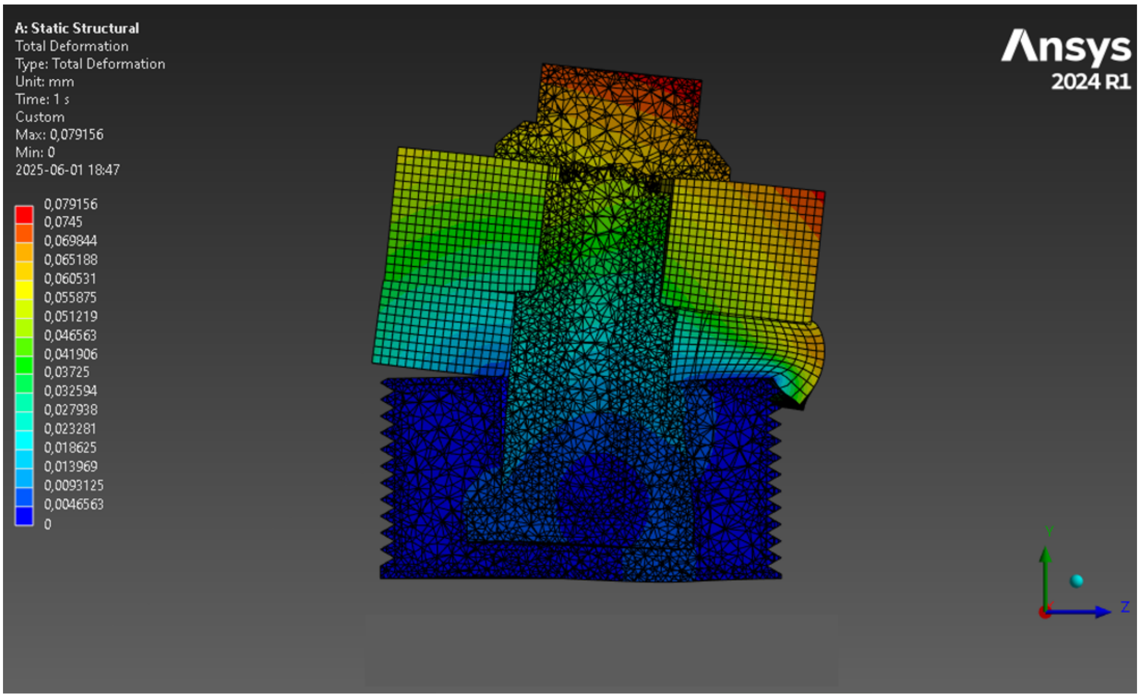
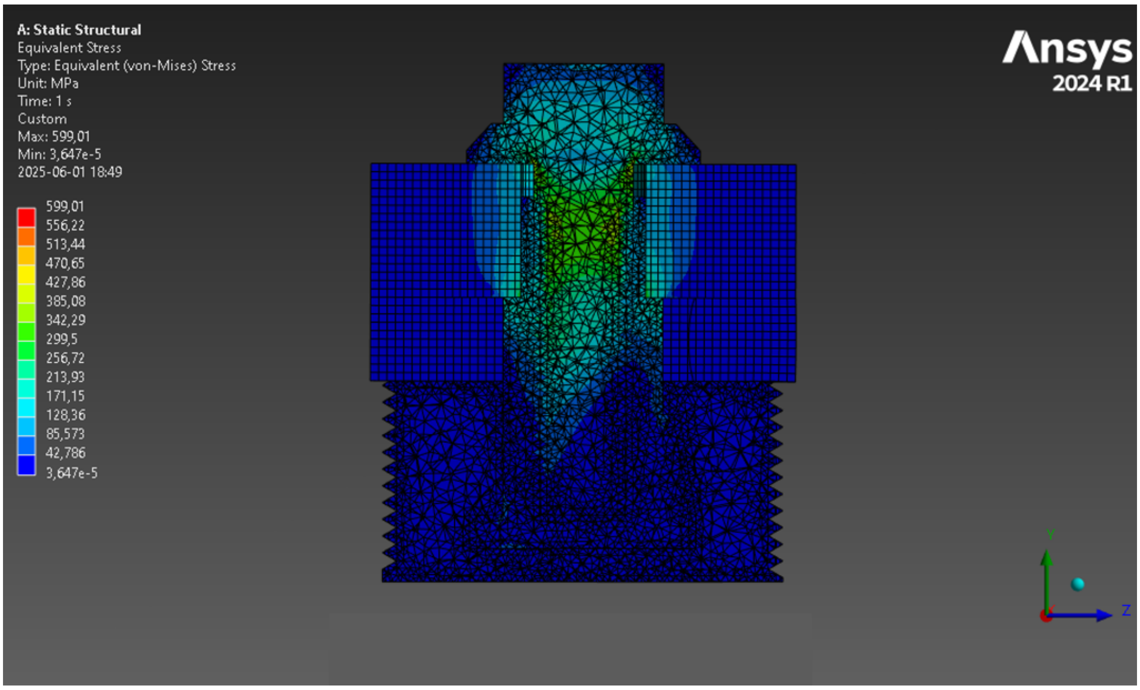


Figure 4.38: Auto-scale (34x) deformation of the assembly for shear strength test

The outcomes showed similar magnitudes of stress and deformation similar to those of the previous simulation, as expected. Once again, the maximum stress occurred near the bolt neck, coinciding with mesh singularities. Although the deformation values were comparable, the deformation pattern differed, occurring in the shearing plane rather than the axial direction observed in the tear-out test. Based on these results and earlier reasoning, the assembly was again deemed structurally sound under the assumed conditions.



A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1 s
Custom
Max: 599,01
Min: 3,647e-5
2025-06-01 18:49

Figure 4.39: Equivalent stress (Von-Mises) of the assembly for shear strength test

The results of this analysis indicated that the design maintained acceptable stress levels under loading, with the majority of stress between the clamped parts due to preload. However, no high stresses were observed in the critical areas of the plastic component where failure could be possible. These findings validate the mechanical robustness of the insert concept. This also provides insight into areas of optimisation in terms of geometry and material selection.

4.14.3 Other details

The results of these simulations indicated that the design maintained acceptable stress levels under applied loads, with most stress concentrated between the clamped components due to the preload. Importantly, no significant stress concentrations were observed in the critical regions of the plastic component where potential failure could occur. Furthermore, the deformation of the insert, leading to the swaying of busbar is also well within the clearance requirements. These findings validate the mechanical robustness of the insert concept and also highlight opportunities for further optimisation in terms of geometry and material selection.

- **Clamping torque:** Analyse and test required torque on bolt-to-anchor to lock the rotation of the inserts caused by the vibration of the truck.

- **Cooling effect on busbars:** How much do the fixation points affect the effective cooling of the busbars in relation to the small area they occupy? How many ^oC does Concept C "add" relative to if there were no fixations or compared to the current solution?

- **Dimensions:** Final dimensions are not stated in the external report. However, the width and depth of the resin depend on the electrical properties of the usage area and therefore it is recommended for relevant component to revise its internal demands on creepage, clearance and dielectric strength.

- **Anchor area:** As visualised in Figure 4.35 and 4.34, the anchor area does not seem to cause problems for the pull-out load nor deformation. Therefore the anchor area could be investigated for further optimisation and down-sizing.

- **Threading pitch:** In the latest iteration, the resin's external threads absorb the load. Therefore, an evaluation of how the threading size affect mechanical robustness through an dynamic analysis could complement the design's optimisation.

- **Step size:** The step size comprises the anchor's contact area with the busbar. This area should be investigated to account for tolerances in the busbar hole and forces applied from the bolt and anchor on the busbar so that deformation does not occur.

- **Bolt/nut size:** Evaluate the minimal bolt size required for function. This was done prior to the project, given that the loads are unaltered, this could be performed to evaluate the usage of the concept in other *Volvo* components than the TVPDC.

- **Resin depth vs pulling force:** Evaluating this could render a more "shallow" design and therefore be a more viable option for bodies using thinner walls.

- **Tolerance stack-up:** Analysing how fine tolerances are needed in the placement of the anchor in elevation and position in relation to the busbar hole and thickness tolerance along with TIM thickness tolerance can provide valuable insight into the allowed roughness of manufacturing the component.

- **Thermal cycling:** Evaluating and testing thermal effects on polymers and analysing how it could the robustness from the dynamic loads in the future. The purpose is to prevent material creep and ensure robustness over time.

5

Conclusion

This project presents the results of a Chalmers-recommended product development process applied to a busbar fixation solution at *Volvo Electromobility*. The initial investigation indicated a need for improvement in some key areas presented as customer needs in Section 4.3. The areas reflected the results of interviews for input for improvement from engineers who were or had been working on the current solution or by interacting components. The input was analysed, interpreted and iterated through the product development process, Section 3. The process yielded several ideas that were merged and refined into three final concepts that were taken to a Concept Gate session for feedback.

After a second concept gate, *one* concept had emerged as the most feasible to succeed. The concept comprises a metal anchor with internal threads for clamping with a metric bolt. The anchor is overmoulded with an insulating plastic or resin according to Figures 4.30 and 4.31 and uses external threads to lock in the TVPDC housing in combination with the friction from the clamping force of the bolt & anchor on the busbar to lock the ”unscrewing” motion caused by vibrations in the truck.

The concept uses a combination of strong mechanical and electrical material in a robust manner that secures the busbar in place and isolates the electricity flowing through the busbar from the TVPDC housing. The design allows for broad design freedom and adaptability to different functions in the truck, and the design freedom, in turn, allows for rougher tolerances and thereby cost efficiency.

In conclusion, the authors recommend investigating *Concept C* on the feasibility of large-scale production along with prototyping in its planned materials. This means analysing tolerance stack-ups and how large tolerances the design allows for if using a realistic *Volvo* supplier. Subsequently, performing tests on electromechanical loads, presented in Section 4.7.4 and the electrical properties of the truck to obtain true performance values of the concept for further evaluation.

Furthermore, the project team suggests evaluating and testing the found characteristics during the investigation physically using adequate materials such as *PA66GF30* and *Aluminium/Steel*. As the next steps in the realisation of the concept, the authors recommend finalising the characteristics presented in Section 4.14.3. Here, the most important points are obtaining an exact value for the clamping torque between the bolt and the busbar, an adequate step size for the contact area between the anchor and the busbar, dimensioning the resin for *downsizing* i.e. using as low dimensions while ensuring robust functionality, and evaluating the threading pitch so that the ”pull-out” does not cause material creep or failure.

6

Discussion

The process of investigating and developing busbar fixation methods yielded valuable insights, not only to how the methodology can be applied to a real product but also to a deeper understanding of the requirements faced by the electrical mobility industry and an. This chapter reflects on the project process and results, identifies areas of improvement, and discusses what might allow or constrain the implementation of the concept.

6.1 Project delimitations

The project started investigating all sections presented in Figure 1.2 but was changed to narrow the focus range to only investigating non-insulated, actively cooled busbars, which inherently rejects potential ideas that could have been created from the other sectors. These ideas, in turn, could have resulted in innovative concepts for *Volvo*. However, as the decision was done by *Volvo* management in accordance with the authors to provide a basis for development within areas of interest with the purpose of developing more detail and quality in the investigated concepts.

6.2 Interviews

Using semi-structured interviews could have affected the resulting answers in that it could pivot the conversation in a direction affected by a potential bias of the interviewer. In addition, the topics and the questions could have been studied further before starting the interview phase.

The risk with this, however, could have been that the project spent a disproportionate amount of time researching that could yield the same results in both cases. The reason for this was that the interviews were focused on working engineers with several years of expertise in the topics, which means they already had understanding of the subject and could interpret and ask what was meant if the questions were not clear.

6.3 Concept screening

Although the concept screening procedure was intended to be as objective and structured as possible, some factors may have unintentionally influenced the result. One such factor was the realisation of the unutilised space beneath the casting, which emerged during the concept generation phase. This discovery naturally drew attention to concepts that made use of this space. In addition, the way screening criteria were selected and prioritised also played a role in shaping the evaluation. Even a single criterion could significantly influence the results. This underlines how, despite following a systematic approach, both the inherent features of the concepts and the framing of the criteria can subtly guide the selection process and impact the final decision.

6.4 Detailed design

The detailed design was prominently affected by the feedback of the engineering team at *Volvo*. This meant that the feedback reflected their engineering intuition more than directly adhering to the internal requirements set by the project or *Volvo*. However, the intuition of the engineers is based on knowledge from previous learnings from other solutions and the testing procedure at the company. This could serve as an argument as being sufficient in some cases, in the data-driven approach of (Ulrich et al., 2011a) it would likely be beneficial to apply more focus to integrate requirements in the initial feedback loop.

6.4.1 Material selection

The material selection process was carried out using a focussed set of material parameters tailored to the functional requirements of each component. For the insulating material, the dielectric strength and yield strength were compared, along with consideration of cost due to the high-volume production context. In the case of the clamping material, the yield strength and the price were prioritised. Although this approach provided a clear basis for initial comparisons, certain relevant material properties were not included in the analysis and could be considered in future evaluations. For insulating materials, factors such as thermal conductivity and long-term working temperatures may significantly influence performance. Similarly, for clamping materials, additional parameters, such as fatigue resistance or manufacturability depending on the process used, could affect the overall suitability. Furthermore, a sustainability comparison between these materials throughout their lifecycle could also be very helpful at this stage. Expanding the selection criteria to incorporate a wider range of properties may yield more comprehensive results and lead to better-informed material choices in future iterations.

6.4.2 CAE

The CAE simulations conducted provided an initial verification of the part's structural performance, focussing on two critical failure modes: tear-out and shear. As discussed in Section 4.14.2 the tear-out simulations were reasonable, however, the shear simulations can be made more realistic and worked on, as the simulated failure mode would only occur in the event of pretension loss, which introduces uncertainty into the results. Although these simulations offered valuable insights to the structural integrity of the design, they represent only a preliminary stage of validation.

Further analysis could improve understanding and confidence in the solution. For instance, thermal simulations of the entire TVPDC assembly that incorporates the proposed design could be performed to evaluate its thermal behaviour compared to the existing configuration. This would help identify potential areas for optimisation. In addition, dynamic simulations, including vibration and shock analysis, could be introduced to investigate how the assembly responds to real-world operational conditions. Such analyses would be particularly useful for assessing the performance of components with relatively lower yield strength, such as the plastic threads, which may be more susceptible to fatigue or failure under dynamic loading.

6.5 Cost

During the project, cost was mentioned as a delimiting factor. The time limit prevented the team from performing a detailed cost calculation, which could have indicated whether the recommended solution was more cost-effective or not. However, the proposed solution is designed to allow rough tolerances while requiring few inexpensive materials that can be manufactured using inexpensive methods, all indicators of cost-efficiency.

Additionally, the recommended solution disconnects the dependency on the system between the fixation and the TIM on (shown in Figure 4.2) the need of a reaction force to fix the busbar. This independence allows the designer to reduce the requirements on the TIM, thereby enabling a wider base for material or supplier selection. This, in turn, can considerably reduce the overall cost of the system.

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A

Gantt Chart

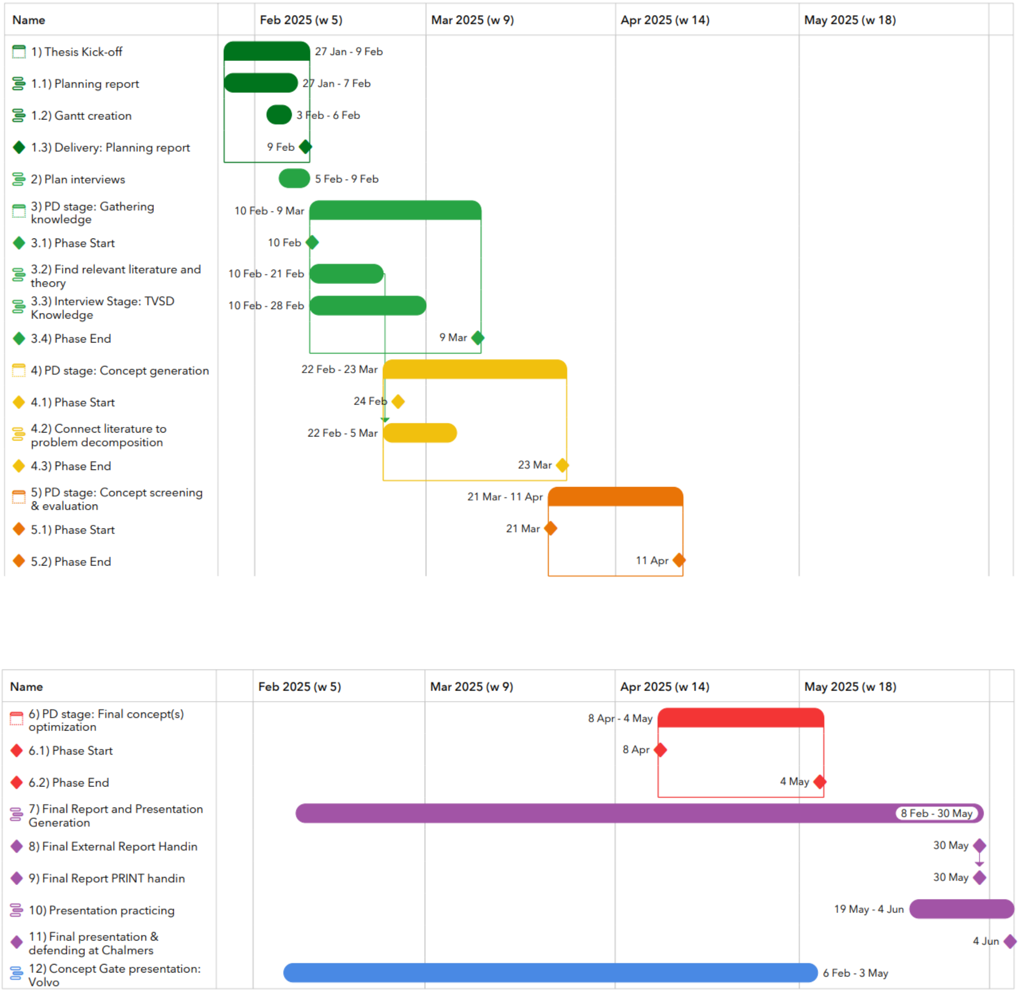


Figure A.1: Planned Schedule throughout the Project Timeline, (2025)

B

Enhanced Function-Means Tree

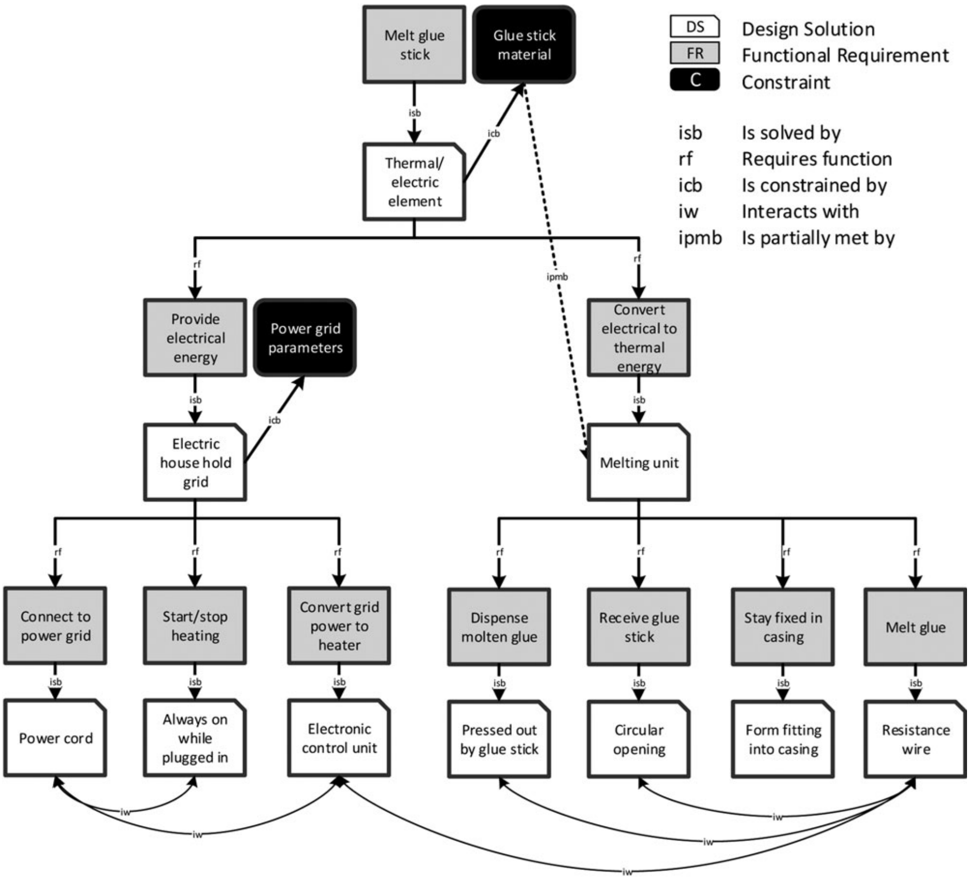


Figure B.1: Visualisation of hierarchy and function of EF-M tree by (Müller et al., 2019)

C

Function-Means Tree

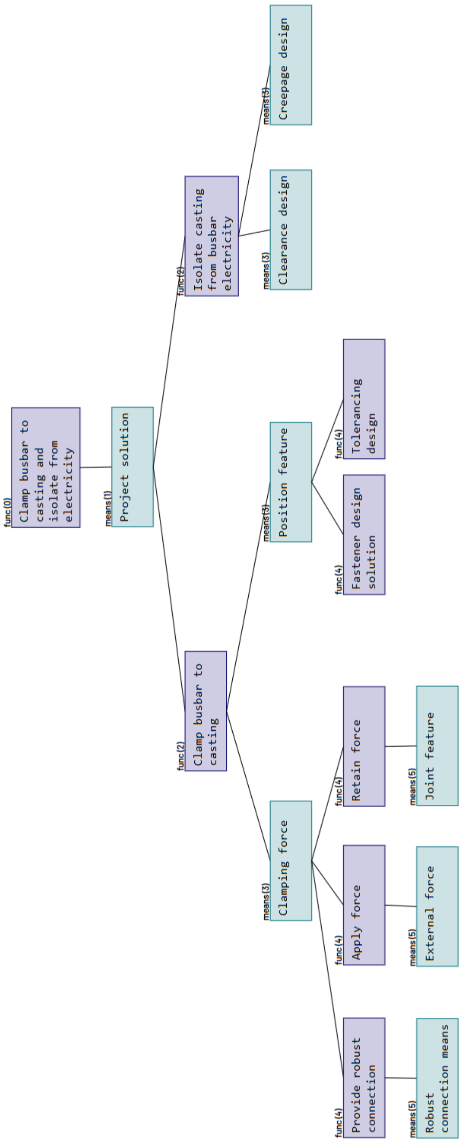


Figure C.1: Full Function-Means Tree. Tool credit: (“Trinity”, 2025)

D

Classification Tree

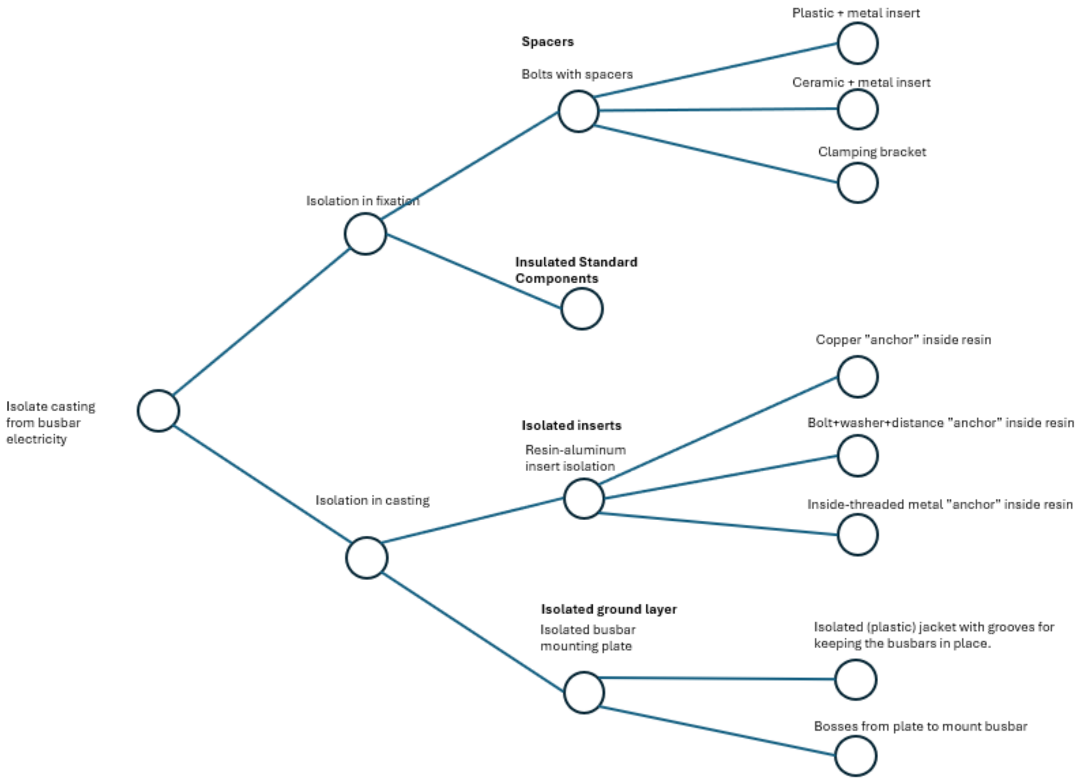
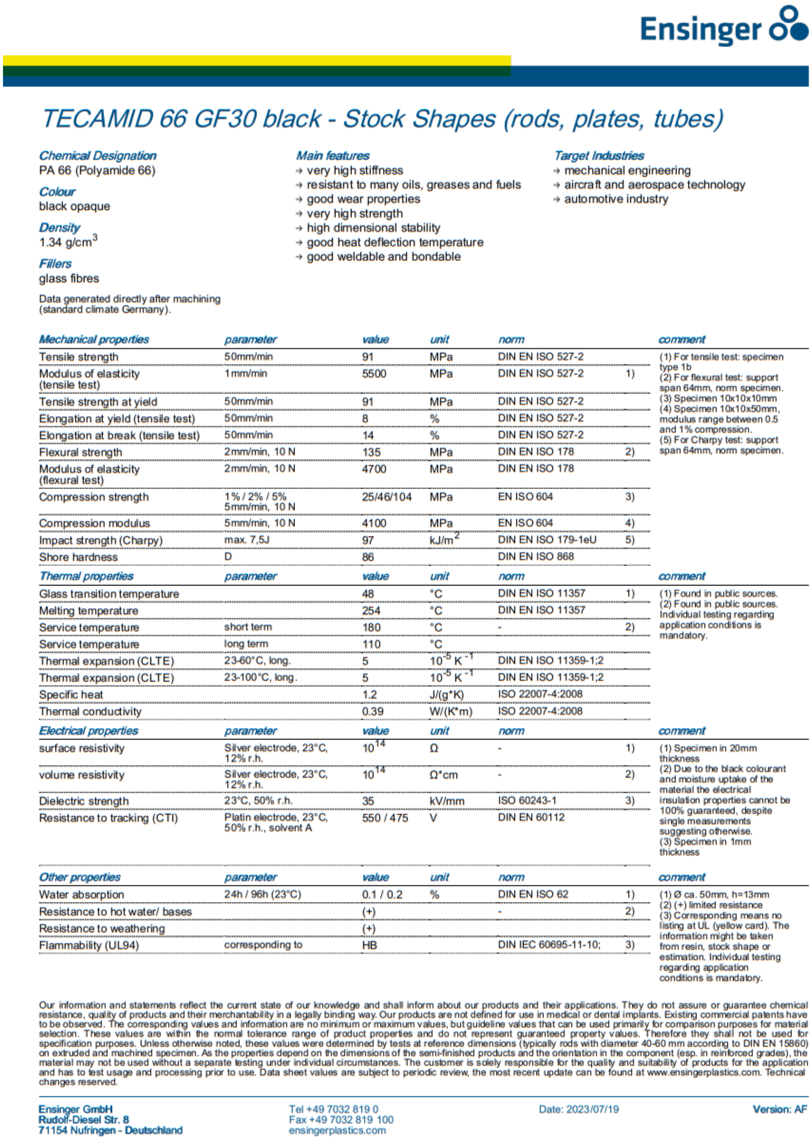


Figure D.1: Classification Tree for insulation

E

Material Data

E.1 PA66 - Polyamide 66



Ensinger

TECAMID 66 GF30 black - Stock Shapes (rods, plates, tubes)

Chemical Designation
PA 66 (Polyamide 66)

Colour
black opaque

Density
1.34 g/cm^3

Fillers
glass fibres

Data generated directly after machining (standard climate Germany).

Main features

- → very high stiffness
- → resistant to many oils, greases and fuels
- → good wear properties
- → very high strength
- → high dimensional stability
- → good heat deflection temperature
- → good weldable and bondable

Target Industries

- → mechanical engineering
- → aircraft and aerospace technology
- → automotive industry

Mechanical properties	*parameter*	*value*	*unit*	*norm*		*comment*
Tensile strength	50mm/min	91	MPa	DIN EN ISO 527-2		(1) For tensile test: specimen type 1b (2) For flexural test: support span 64mm, norm specimen. (3) Specimen 10x10x10mm (4) Specimen 10x10x50mm, modulus range between 0.5 and 1% compression. (5) For Charpy test: support span 64mm, norm specimen.
Modulus of elasticity (tensile test)	1mm/min	5500	MPa	DIN EN ISO 527-2	1)	
Tensile strength at yield	50mm/min	91	MPa	DIN EN ISO 527-2		
Elongation at yield (tensile test)	50mm/min	8	%	DIN EN ISO 527-2		
Elongation at break (tensile test)	50mm/min	14	%	DIN EN ISO 527-2		
Flexural strength	2mm/min, 10 N	135	MPa	DIN EN ISO 178	2)	
Modulus of elasticity (flexural test)	2mm/min, 10 N	4700	MPa	DIN EN ISO 178		
Compression strength	1% / 2% / 5% 5mm/min, 10 N	25/46/104	MPa	EN ISO 604	3)	
Compression modulus	5mm/min, 10 N	4100	MPa	EN ISO 604	4)	
Impact strength (Charpy)	max. 7,5J	97	kJ/m^2	DIN EN ISO 179-1eU	5)	
Shore hardness	D	86		DIN EN ISO 868		

Thermal properties	*parameter*	*value*	*unit*	*norm*		*comment*
Glass transition temperature		48	°C	DIN EN ISO 11357	1)	(1) Found in public sources. (2) Found in public sources. Individual testing regarding application conditions is mandatory.
Melting temperature		254	°C	DIN EN ISO 11357		
Service temperature	short term	180	°C	-	2)	
Service temperature	long term	110	°C			
Thermal expansion (CLTE)	23-60°C, long.	5	10^{-5} K^{-1}	DIN EN ISO 11359-1;2		
Thermal expansion (CLTE)	23-100°C, long.	5	10^{-5} K^{-1}	DIN EN ISO 11359-1;2		
Specific heat		1.2	J/(g*K)	ISO 22007-4:2008		
Thermal conductivity		0.39	W/(K*m)	ISO 22007-4:2008		

Electrical properties	*parameter*	*value*	*unit*	*norm*		*comment*
surface resistivity	Silver electrode, 23°C, 12% r.h.	10^{14}	Ω	-	1)	(1) Specimen in 20mm thickness (2) Due to the black colourant and moisture uptake of the material the electrical insulation properties cannot be 100% guaranteed, despite single measurements suggesting otherwise. (3) Specimen in 1mm thickness
volume resistivity	Silver electrode, 23°C, 12% r.h.	10^{14}	Ω*cm	-	2)	
Dielectric strength	23°C, 50% r.h.	35	kV/mm	ISO 60243-1	3)	
Resistance to tracking (CTI)	Platin electrode, 23°C, 50% r.h., solvent A	550 / 475	V	DIN EN 60112		

Other properties	*parameter*	*value*	*unit*	*norm*		*comment*
Water absorption	24h / 96h (23°C)	0.1 / 0.2	%	DIN EN ISO 62	1)	(1) Ø ca. 50mm, h=13mm (2) (+) limited resistance (3) Corresponding means no listing at UL (yellow card). The information might be taken from resin, stock shape or estimation. Individual testing regarding application conditions is mandatory.
Resistance to hot water/ bases		(+)		-	2)	
Resistance to weathering		(+)				
Flammability (UL94)	corresponding to	HB		DIN IEC 60695-11-10;	3)	

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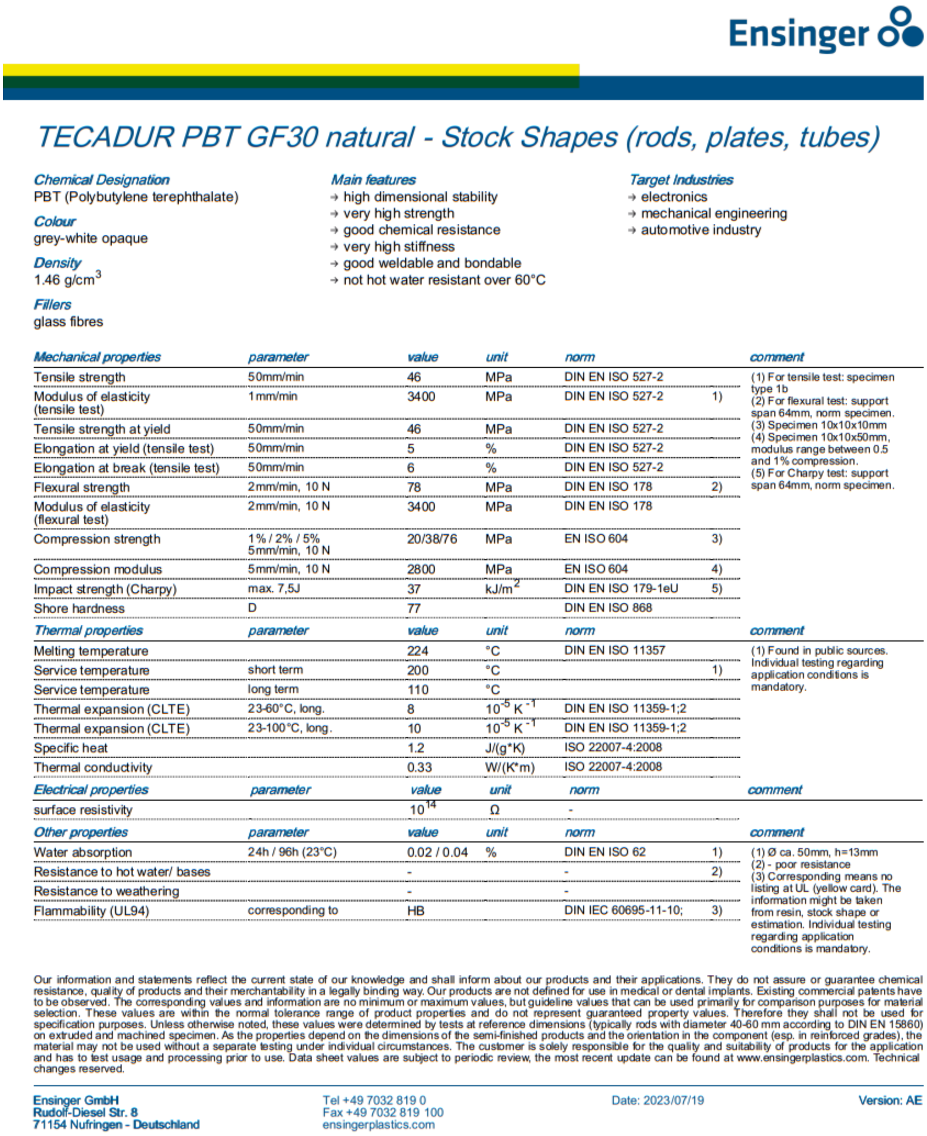
Version: AF

Figure E.1: Ensinger plastics *TECAMID 66 GF30* material data sheet ("TECAMID 66 GF30 black", 2023).

E.2 PBT - (Polybutylene terephthalate)



Ensinger

TECADUR PBT GF30 natural - Stock Shapes (rods, plates, tubes)

Chemical Designation
PBT (Polybutylene terephthalate)

Colour
grey-white opaque

Density
1.46 g/cm^3

Fillers
glass fibres

Main features
- → high dimensional stability
- → very high strength
- → good chemical resistance
- → very high stiffness
- → good weldable and bondable
- → not hot water resistant over 60°C

Target Industries
- → electronics
- → mechanical engineering
- → automotive industry

Mechanical properties	*parameter*	*value*	*unit*	*norm*		*comment*
Tensile strength	50mm/min	46	MPa	DIN EN ISO 527-2		(1) For tensile test: specimen type 1b (2) For flexural test: support span 64mm, norm specimen. (3) Specimen 10x10x10mm (4) Specimen 10x10x50mm, modulus range between 0.5 and 1% compression. (5) For Charpy test: support span 64mm, norm specimen.
Modulus of elasticity (tensile test)	1mm/min	3400	MPa	DIN EN ISO 527-2	1)	
Tensile strength at yield	50mm/min	46	MPa	DIN EN ISO 527-2		
Elongation at yield (tensile test)	50mm/min	5	%	DIN EN ISO 527-2		
Elongation at break (tensile test)	50mm/min	6	%	DIN EN ISO 527-2		
Flexural strength	2mm/min, 10 N	78	MPa	DIN EN ISO 178	2)	
Modulus of elasticity (flexural test)	2mm/min, 10 N	3400	MPa	DIN EN ISO 178		
Compression strength	1% / 2% / 5% 5mm/min, 10 N	20/38/76	MPa	EN ISO 604	3)	
Compression modulus	5mm/min, 10 N	2800	MPa	EN ISO 604	4)	
Impact strength (Charpy)	max. 7,5J	37	kJ/m^2	DIN EN ISO 179-1eU	5)	
Shore hardness	D	77		DIN EN ISO 868		

Thermal properties	*parameter*	*value*	*unit*	*norm*		*comment*
Melting temperature		224	°C	DIN EN ISO 11357		(1) Found in public sources. Individual testing regarding application conditions is mandatory.
Service temperature	short term	200	°C		1)	
Service temperature	long term	110	°C			
Thermal expansion (CLTE)	23-60°C, long.	8	10^{-5} K^{-1}	DIN EN ISO 11359-1;2		
Thermal expansion (CLTE)	23-100°C, long.	10	10^{-5} K^{-1}	DIN EN ISO 11359-1;2		
Specific heat		1.2	J/(g*K)	ISO 22007-4:2008		
Thermal conductivity		0.33	W/(K*m)	ISO 22007-4:2008		

Electrical properties	*parameter*	*value*	*unit*	*norm*		*comment*
surface resistivity		10^{14}	Ω	-		

Other properties	*parameter*	*value*	*unit*	*norm*		*comment*
Water absorption	24h / 96h (23°C)	0.02 / 0.04	%	DIN EN ISO 62	1)	(1) Ø ca. 50mm, h=13mm (2) - poor resistance (3) Corresponding means no listing at UL (yellow card). The information might be taken from resin, stock shape or estimation. Individual testing regarding application conditions is mandatory.
Resistance to hot water/ bases		-		-	2)	
Resistance to weathering		-		-		
Flammability (UL94)	corresponding to	HB		DIN IEC 60695-11-10;	3)	

Our information and statements reflect the current state of our knowledge and shall inform about our products and their applications. They do not assure or guarantee chemical resistance, quality of products and their merchantability in a legally binding way. Our products are not defined for use in medical or dental implants. Existing commercial patents have to be observed. The corresponding values and information are no minimum or maximum values, but guideline values that can be used primarily for comparison purposes for material selection. These values are within the normal tolerance range of product properties and do not represent guaranteed property values. Therefore they shall not be used for specification purposes. Unless otherwise noted, these values were determined by tests at reference dimensions (typically rods with diameter 40-60 mm according to DIN EN 15860) on extruded and machined specimen. As the properties depend on the dimensions of the semi-finished products and the orientation in the component (esp. in reinforced grades), the material may not be used without a separate testing under individual circumstances. The customer is solely responsible for the quality and suitability of products for the application and has to test usage and processing prior to use. Data sheet values are subject to periodic review, the most recent update can be found at www.ensingerplastics.com. Technical changes reserved.

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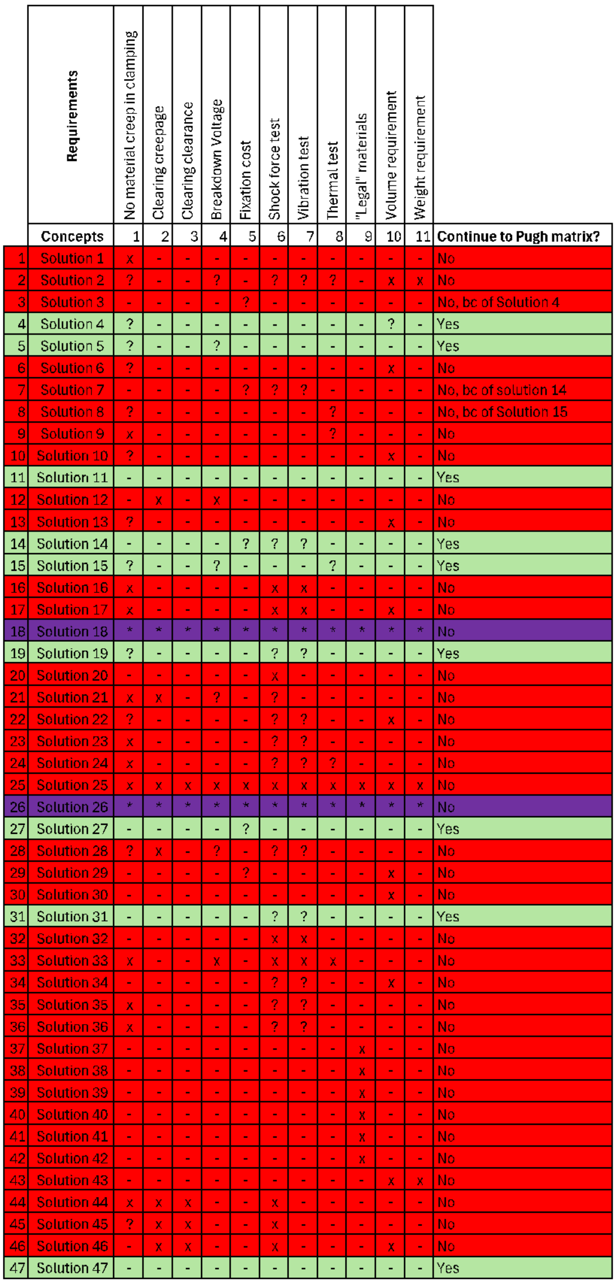
Date: 2023/07/19

Version: AE

Figure E.2: Ensinger plastics *TECADUR PBT GF30* material data sheet (“TECADUR PBT GF30 natural -”, 2023).

F

Elimination Matrix

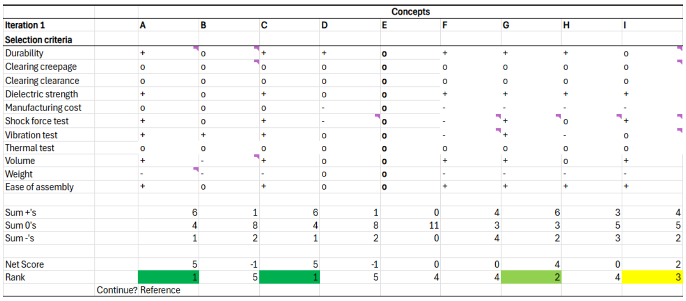


	Requirements	No material creep in clamping	Clearing creepage	Clearing clearance	Breakdown Voltage	Fixation cost	Shock force test	Vibration test	Thermal test	"Legal" materials	Volume requirement	Weight requirement	
	Concepts	1	2	3	4	5	6	7	8	9	10	11	**Continue to Pugh matrix?**
1	Solution 1	x	-	-	-	-	-	-	-	-	-	-	No
2	Solution 2	?	-	-	?	-	?	?	?	-	x	x	No
3	Solution 3	-	-	-	-	?	-	-	-	-	-	-	No, bc of Solution 4
4	Solution 4	?	-	-	-	-	-	-	-	-	?	-	Yes
5	Solution 5	?	-	-	?	-	-	-	-	-	-	-	Yes
6	Solution 6	?	-	-	-	-	-	-	-	-	x	-	No
7	Solution 7	-	-	-	-	?	?	?	-	-	-	-	No, bc of solution 14
8	Solution 8	?	-	-	-	-	-	-	?	-	-	-	No, bc of Solution 15
9	Solution 9	x	-	-	-	-	-	-	?	-	-	-	No
10	Solution 10	?	-	-	-	-	-	-	-	-	x	-	No
11	Solution 11	-	-	-	-	-	-	-	-	-	-	-	Yes
12	Solution 12	-	x	-	x	-	-	-	-	-	-	-	No
13	Solution 13	?	-	-	-	-	-	-	-	-	x	-	No
14	Solution 14	-	-	-	-	?	?	?	-	-	-	-	Yes
15	Solution 15	?	-	-	?	-	-	-	?	-	-	-	Yes
16	Solution 16	x	-	-	-	-	x	x	-	-	-	-	No
17	Solution 17	x	-	-	-	-	x	x	-	-	x	-	No
18	Solution 18	*	*	*	*	*	*	*	*	*	*	*	No
19	Solution 19	?	-	-	-	-	?	?	-	-	-	-	Yes
20	Solution 20	-	-	-	-	-	x	-	-	-	-	-	No
21	Solution 21	x	x	-	?	-	?	-	-	-	-	-	No
22	Solution 22	?	-	-	-	-	?	?	-	-	x	-	No
23	Solution 23	x	-	-	-	-	?	?	-	-	-	-	No
24	Solution 24	x	-	-	-	-	?	?	?	-	-	-	No
25	Solution 25	x	x	x	x	x	x	x	x	x	x	x	No
26	Solution 26	*	*	*	*	*	*	*	*	*	*	*	No
27	Solution 27	-	-	-	-	?	-	-	-	-	-	-	Yes
28	Solution 28	?	x	-	?	-	?	?	-	-	-	-	No
29	Solution 29	-	-	-	-	?	-	-	-	-	x	-	No
30	Solution 30	-	-	-	-	-	-	-	-	-	x	-	No
31	Solution 31	-	-	-	-	-	?	?	-	-	-	-	Yes
32	Solution 32	-	-	-	-	-	x	x	-	-	-	-	No
33	Solution 33	x	-	-	x	-	x	x	x	-	-	-	No
34	Solution 34	-	-	-	-	-	?	?	-	-	x	-	No
35	Solution 35	x	-	-	-	-	?	?	-	-	-	-	No
36	Solution 36	x	-	-	-	-	?	?	-	-	-	-	No
37	Solution 37	-	-	-	-	-	-	-	-	x	-	-	No
38	Solution 38	-	-	-	-	-	-	-	-	x	-	-	No
39	Solution 39	-	-	-	-	-	-	-	-	x	-	-	No
40	Solution 40	-	-	-	-	-	-	-	-	x	-	-	No
41	Solution 41	-	-	-	-	-	-	-	-	x	-	-	No
42	Solution 42	-	-	-	-	-	-	-	-	x	-	-	No
43	Solution 43	-	-	-	-	-	-	-	-	-	x	x	No
44	Solution 44	x	x	x	-	-	x	-	-	-	-	-	No
45	Solution 45	?	x	x	-	-	x	-	-	-	-	-	No
46	Solution 46	-	x	x	-	-	x	-	-	-	x	-	No
47	Solution 47	-	-	-	-	-	-	-	-	-	-	-	Yes

Figure F.1: Elimination Matrix

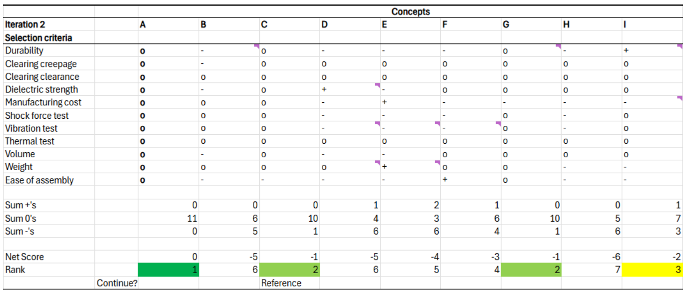
G

Pugh Screening Matrix



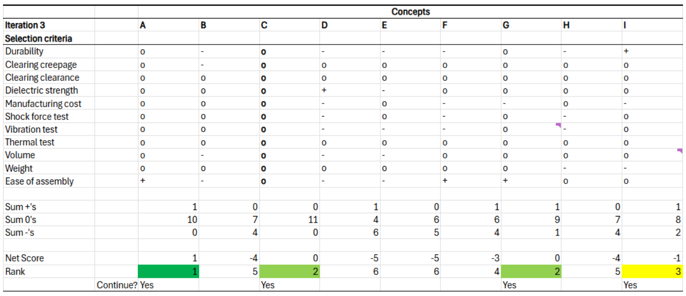
		Concepts								
Iteration 1		**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Selection criteria										
Durability		+	o	+	+	o	+	+	+	o
Clearing creepage		o	o	o	o	o	o	o	o	o
Clearing clearance		o	o	o	o	o	o	o	o	o
Dielectric strength		+	o	+	o	o	+	+	+	+
Manufacturing cost		o	o	o	-	o	-	-	-	-
Shock force test		+	o	+	-	o	-	+	o	+
Vibration test		+	+	+	o	o	-	+	-	o
Thermal test		o	o	o	o	o	o	o	o	o
Volume		+	-	+	o	o	+	+	o	+
Weight		-	-	-	o	o	-	-	-	-
Ease of assembly		+	o	+	o	o	+	+	+	+
Sum +'s		6	1	6	1	0	4	6	3	4
Sum 0's		4	8	4	8	11	3	3	5	5
Sum -'s		1	2	1	2	0	4	2	3	2
Net Score		5	-1	5	-1	0	0	4	0	2
Rank		1	5	1	5	4	4	2	4	3
	Continue?	Reference								

Figure G.1: *Pugh matrix* iteration 1.



		Concepts								
Iteration 2		**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Selection criteria										
Durability		o	-	o	-	-	-	o	-	+
Clearing creepage		o	-	o	o	o	o	o	o	o
Clearing clearance		o	o	o	o	o	o	o	o	o
Dielectric strength		o	-	o	+	-	o	o	o	o
Manufacturing cost		o	o	o	-	+	-	-	-	-
Shock force test		o	o	o	-	-	-	o	-	o
Vibration test		o	o	o	-	-	-	o	-	o
Thermal test		o	o	o	o	o	o	o	o	o
Volume		o	-	o	-	-	o	o	o	o
Weight		o	o	o	o	+	o	o	-	-
Ease of assembly		o	-	-	-	-	+	o	-	-
Sum +'s		0	0	0	1	2	1	0	0	1
Sum 0's		11	6	10	4	3	6	10	5	7
Sum -'s		0	5	1	6	6	4	1	6	3
Net Score		0	-5	-1	-5	-4	-3	-1	-6	-2
Rank		1	6	2	6	5	4	2	7	3
	Continue?			Reference						

Figure G.2: *Pugh matrix* iteration 2.

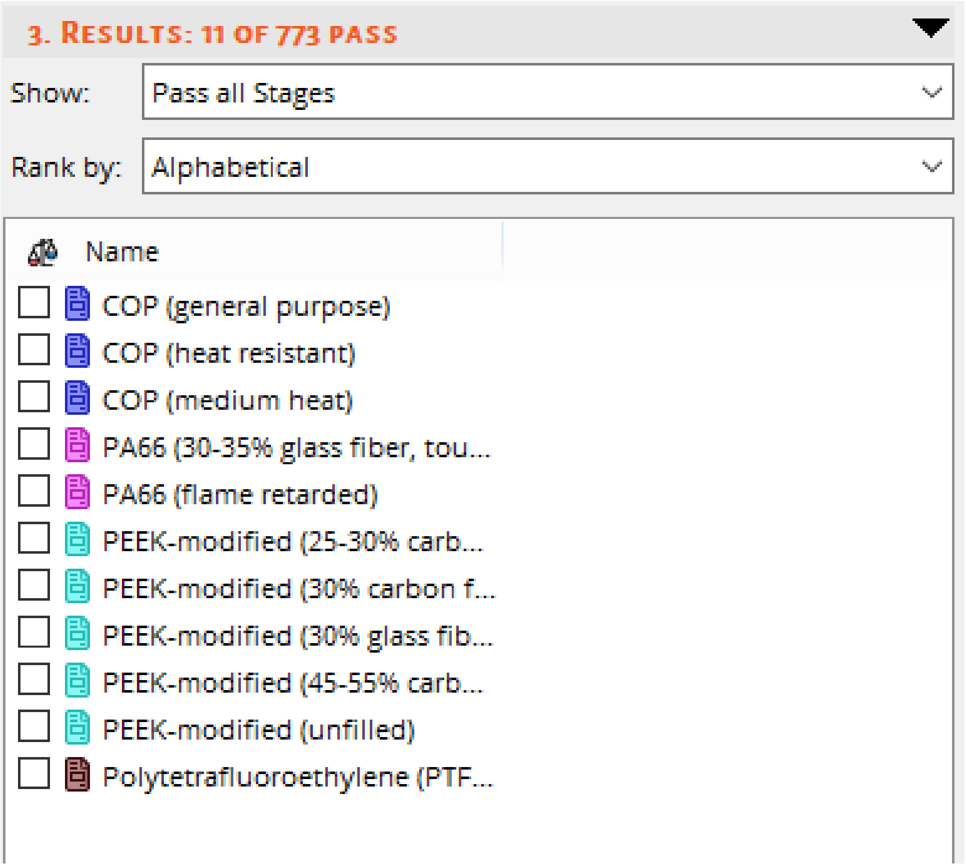


		Concepts								
Iteration 3		**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Selection criteria										
Durability		o	-	o	-	-	-	o	-	+
Clearing creepage		o	-	o	o	o	o	o	o	o
Clearing clearance		o	o	o	o	o	o	o	o	o
Dielectric strength		o	o	o	+	-	o	o	o	o
Manufacturing cost		o	o	o	-	o	-	-	o	-
Shock force test		o	o	o	-	o	-	o	-	o
Vibration test		o	o	o	-	-	-	o	-	o
Thermal test		o	o	o	o	o	o	o	o	o
Volume		o	-	o	-	-	o	o	o	o
Weight		o	o	o	o	o	o	o	-	-
Ease of assembly		+	-	o	-	-	+	+	o	o
Sum +'s		1	0	0	1	0	1	1	0	1
Sum 0's		10	7	11	4	6	6	9	7	8
Sum -'s		0	4	0	6	5	4	1	4	2
Net Score		1	-4	0	-5	-5	-3	0	-4	-1
Rank		1	5	2	6	6	4	2	5	3
	Continue?	Yes		Yes				Yes		Yes

Figure G.3: *Pugh matrix* iteration 3.

H

Material Investigation



3. RESULTS: 11 OF 773 PASS

Show: Pass all Stages

Rank by: Alphabetical

Name

☐ COP (general purpose)
☐ COP (heat resistant)
☐ COP (medium heat)
☐ PA66 (30-35% glass fiber, tou...
☐ PA66 (flame retarded)
☐ PEEK-modified (25-30% carb...
☐ PEEK-modified (30% carbon f...
☐ PEEK-modified (30% glass fib...
☐ PEEK-modified (45-55% carb...
☐ PEEK-modified (unfilled)
☐ Polytetrafluoroethylene (PTF...

Figure H.1: List of passed materials. Tool credit: *Granta*

I

Assembly Sequence

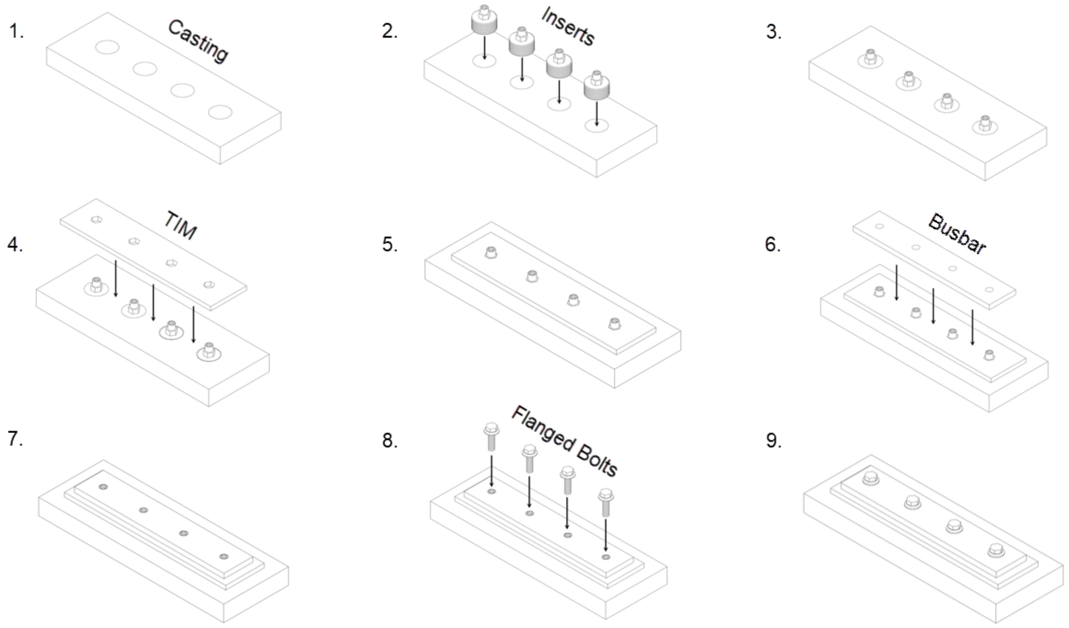


Figure I.1: List of passed materials. Tool credit: *Granta*

J

Tear-out strength test results for steel anchor

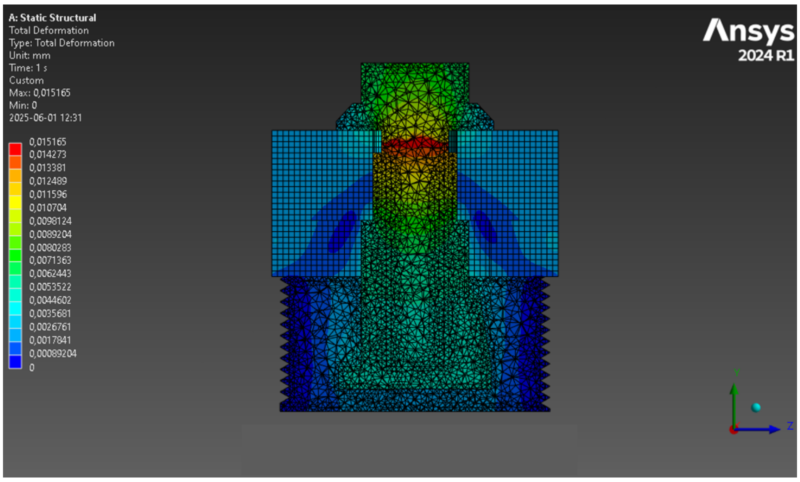


Figure J.1: True scale deformation of the assembly for tear-out strength test

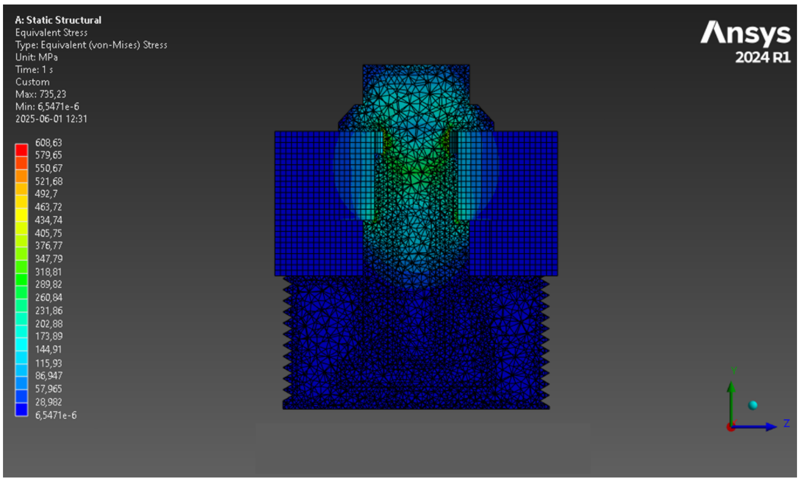


Figure J.2: Equivalent stress (Von-Mises) of the assembly for tear-out strength test

K

Shear strength test results for steel anchor

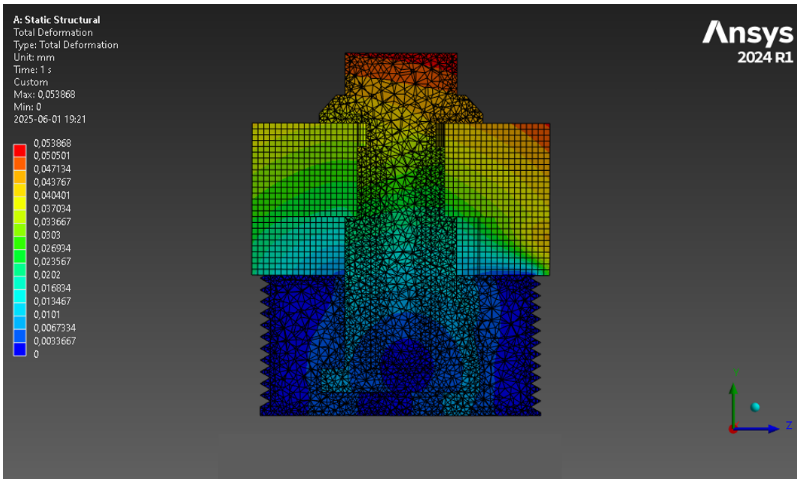


Figure K.1: True scale deformation of the assembly for shear strength test

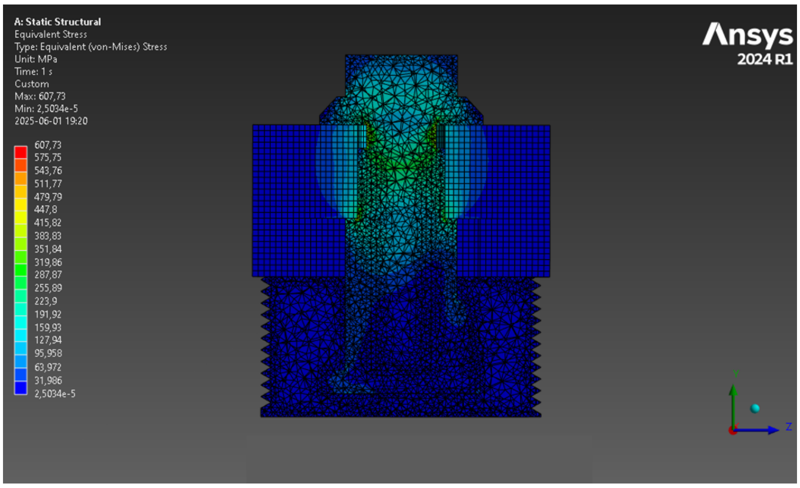


Figure K.2: Equivalent stress (Von-Mises) of the assembly for shear strength test

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