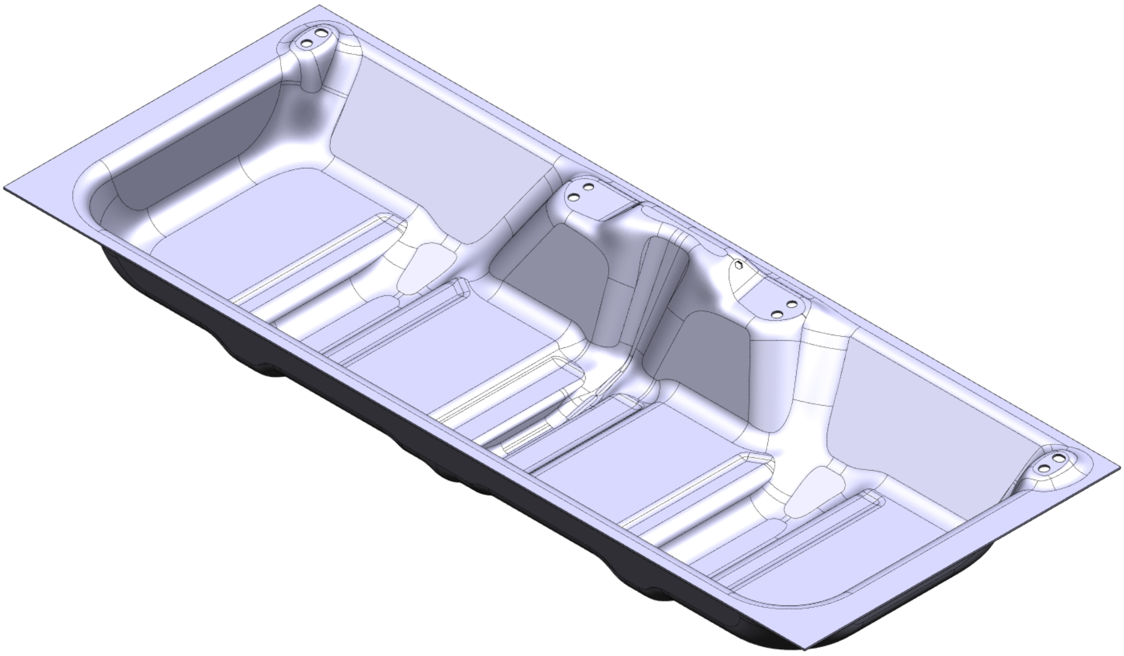

Design a High-Voltage Battery Enclosure System using a new manufacturing method

Designing a battery enclosure component by hot form quenching using high strength aluminium.

Master's thesis in Product Development

CHARLIE NILSSON, DANIEL OSORIO

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
www.chalmers.se

Master's thesis 2024

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A case study of a redesign of a component for the battery tray

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Abstract

Volvo Cars, a major company in Sweden and Europe, is partnering with Impression Technologies to develop a key part of the battery tray using a new method called Hot Form Quenching. This new method could be used for many parts of the vehicle, helping to reduce weight, improve performance, and move the company closer to its sustainability goals.

This master thesis aims to explore the process of transforming a component called footgarage originally developed for High Pressure Die Casting into a sheet metal component and covering several assessment points like function performance, sustainability, part price, investment cost, manufacturing process impacts, time to market, and material base. A comparison between these two concepts will tell if this new process has a future at Volvo Cars.

Acknowledgements

We would like to extend our gratitude to the professionals who help us with this project from the beginning to its end but specially to Magnus Bertilson, Patrik Olsson, and to the engineers experts from different departments such as Welding, CAE, Sustainability, Manufacturing, NVH, Ergonomics, Standard Parts among others for their support and insightful discussions.

A Special thanks to Impression Technologies team for their generously support through the simulation and optimization process. Thanks to their contribution, this project and the Battery Enclosure Department gain expertise about concept creation, design and optimization in a new manufacturing method.

Finally, we extend our appreciation to Christer Persson for providing valuable feedback to the structure and formatting of this document. This thesis work would not have been possible without the collective contributions of all those mentioned before.

Our most sincere gratitude.

Charlie Nilsson, Daniel Osorio. Gothenburg, May 2024

List of Acronyms

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

BES	Battery Energy Storage
BEV	Battery Electric Vehicle
DER	Distributed Energy Resource
ITL	Impression Technologies
CAE	Computer Aided Engineering
NVH	Noise, Vibration and Harshness
OEM	Original Equipment Manufacturers
HFQ	Hot Form Quenching
HPDC	High Pressure Die Cast
LCA	Life Cycle Assessment

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1 Introduction

As the global automotive industry transitions towards a higher proportion of battery electric vehicles (BEVs) on the roads, it's becoming increasingly evident what user demands these vehicles entail. Among these demands, certain requirements stand out as critical for original equipment manufacturers (OEMs) to capture a significant share of the market among typical consumers in the automotive sector. Two of these requirements are price and range, both of which are closely tied to the weight of the vehicle.

Reducing the weight of a car has significant implications for both cost and range, which are key considerations for consumers. A lighter vehicle typically translates to an extended range, as less energy is required to propel it. Reducing the amount of heavy materials used in manufacturing directly contributes to lower costs, particularly in the case of metals. So, by minimizing the use of heavy metal components in a car, OEMs can directly influence both cost and range, thereby enhancing the attractiveness of their BEVs to consumers.

This study examines the possibilities of reducing costs and weight in the battery of a BEV by attempting to recreate a large cast aluminum component in sheet metal. This is not entirely trivial as the cast part serves many different functions, which in turn means that high demands are placed on the geometry and strength of the component. When considering these two requirements together, sheet metal is not typically the first thing that comes to mind. While forming high-strength aluminum is indeed possible to some extent, shaping it into complex geometries is anything but simple.

The primary challenge with high-strength aluminum alloys used in structural sheet metal parts is that they're not easy to shape and tend to spring back when formed at room temperature. This makes it difficult to create complex shapes using traditional cold forming methods. Attempting to shape them at higher temperatures solves the shaping problem but can cause the alloy to age prematurely. This early aging may lead to unexpected changes in the alloy's mechanical properties. To counteract this, we need to apply a controlled aging treatment separately after forming. So, we address the problem, but in doing so, we introduce another: the controlled aging process can cause the formed part to warp.

This is where Hot Formed Quenching (HFQ) comes in. HFQ combines hot forming and quenching within the press itself [1]. This solves the remaining issue of warping in hot forming aluminum. So, HFQ offers a combined solution to the problems that arise when working with high-strength aluminum alloys. It shapes the aluminum at elevated temperatures to reduce spring back and controls the aging process without causing warping by quenching the part while it remains in the press.

HFQ is a relatively new manufacturing method that promises increased design freedom, reduced spring back, greater lightweighting, and lower costs. As Volvo Cars transitions towards a fully electric era, these advantages become crucial. Lighter vehicles and lower costs directly impact what customers value most when buying an electric car: mileage and price.

1.1 Aims and objective

The specific objective of the project was to redesign a cast high-voltage enclosure part with a the HFQ manufacturing technology and to perform a comparison between the cast part and the new HFQ part, to assess the potential benefits of HFQ.

The component in question is referred to as the footgarage. It is a structural high-pressure die-cast (HPDC) part of a BEV battery, designed primarily to increase legroom for rear passengers. This is accomplished by carving out a portion of the battery's interior to create a tub-like structure within the battery itself. The HPDC footgarage concept is depicted in red in Figure 1.1 below.

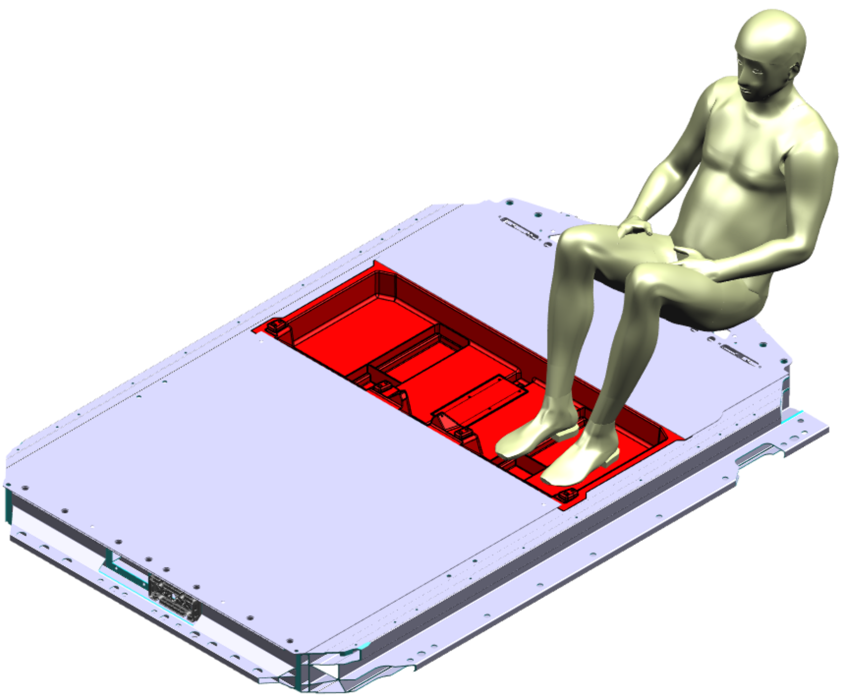


Figure 1.1: The original HPDC concept, which the project recreated using HFQ manufacturing, is highlighted in red.

The aim of the project was to develop a footgarage concept manufacturable with HFQ and to compare the HFQ concept against the HPDC concept at seven different assessment points, see Table 1.1

Description
Function performance
Sustainability
Part price
Investment cost
Manufacturing process impacts
Time to market
Material base

Table 1.1: The seven different assessment points

In addition to these assessment points, this project also aimed to establish a valuable partnership with the proprietary owner and supplier of the HFQ technology and expand the knowledge within R&D department at Volvo Cars.

2
Theory

In the following chapter, theories and concepts relevant to the thesis will be described. The chapter aims to provide the necessary knowledge required to follow the rest of the report.

2.1 Heat treatment

Heat treatment is a process that involves heating a material to a specific temperature, followed by a controlled cooling media or environment and, in some cases, reheating. This process is designed to alter the physical and mechanical properties of the material to enhance its performance, durability, and other desired characteristics [2]. The cooling rate influences the final micro-structure and the mechanical properties of the material, however, some heat treatments involve a secondary heating stage or tempering, where the material is reheated to a specific temperature to achieve a balance between hardness and toughness.

2.2 Solution heat treatment

The Solution Heat Treatment (SHT) is a specific type of heat treatment where the temperature is carefully controlled to dissolve hardening precipitates inside the microstructure of a material, inducing important changes to the alloy [3]. This process not only enhances the material's formability but also improves its ability to withstand extensive plastic deformation without the risk of cracking. An example of this temperature is 525°C which is applicable to 6xxx aluminum series which represents the upper limit that the material should attain before initiating the following cooling process. The precision and control of the temperature during SHT is a key process for achieving the desired mechanical properties for an optimal performance of the final product .

2.3 Hot Form Quenching

The HFQ process is a relatively new sheet metal forming process that can be used to produce complex-shaped components from high-strength aluminum, such as the

6000 and 7000 series. It works by combining hot forming and heat treatment processes into one operation. The process consists of four main steps [4].

Step 1 Before forming, the metal blank is heated to its solution heat treatment temperature. This is done to achieve a homogenized microstructure where the precipitates fully dissolve in the aluminum matrix. This step is taken to increase the material's formability.

Step 2 The blank is then transferred to a press with special dies that have coolant lines running through them to keep them cold. The dies stamp the part at high speed to facilitate material strain rate hardening and thereby enhance drawability. Another reason is to prevent excessive heat transfer to the tool before the stamping is finished, thereby preserving the material's formability until the forming is completed.

Step 3 The formed component is held within the cooled dies to rapidly cool it to a low temperature (quench) to ensure that the supersaturated solid solution microstructure is attained. This is the desirable microstructure that provides the wanted strength of the formed material.

Step 4 If the material is heat-treatable, then the formed component can be artificially aged to achieve finely distributed precipitates. This will give the material and the part its full strength.

2.4 High Pressure Die Casting

High Pressure Die Casting is a widely used manufacturing process for the production of structural components with complex shapes used in many different industries, specially in the automotive industry. The process involves injecting molten metal, into a precision-designed mold at high pressures to create a detailed final product or part [5]. The processes of HPDC can be summarized into the following steps:

Step 1 Die preparation. Heating of the two hardened steel dies, to exact temperature before injecting the molten metal.

Step 2 Injection of molten metal. The dies are clamped together and molten metal is added into the cavity at high pressures.

Step 3 Cooling. After the injection, the molten metal rapidly cools and solidifies within the die cavity. The cooling rate is carefully controlled to achieve the desired material properties.

Step 4 Ejection. Once the material has solidified, the dies are opened and the created part is ejected from the mold. Some extra work could be applied to the final piece to comply design specifications.

Step 5 Recycling and reusing. Any scrap material generated is gathered and recycled.

2.5 Aluminum refinement process

The aluminum extraction and refinement processes begin with treating bauxite by using sodium hydroxide to produce purified alumina. This involves filtration, chemical treatment, and crystallization, resulting in a supersaturated sodium aluminate liquor [6]. Then, the liquor is heated to produce anhydrous aluminum oxide, which is then sent to primary smelters for further processing including electrolytic reduction of aluminum oxide in molten cryolite.

2.6 Sustainable aluminium

Sustainable aluminum is the description for a fully recycled aluminum as a result of using 95% less energy for its production aiming to minimize environmental impact, conserving resources, while ensuring same mechanical properties [7]. This impacts CO2 emissions, and minimizes the extraction of new raw materials. This aligns with the principles of a circular economy, integrating social and ethical standards into the aluminum industry's operational framework.

2.7 Aluminum recycling

Secondary aluminum production consists of re-melting scrap sourced from different industries. The scrap is systematically sorted by alloy type, employing practical methods like magnetic separation, air separation, eddy current separation, dense media separation, manual hand sorting, and hot crushing [6]. To optimize emissions control, energy efficiency, and metallic yield, contaminants like oil, paint, and coatings on the scrap are eliminated through the use of centrifuges or de-coating machines. The secondary aluminum sector is on the rise, consuming less than 10% of the energy used for primary production resulting in very low environmental impact.

2.8 Life Cycle Assessment

Life Cycle Assessment (LCA) serves as a comprehensive tool for evaluating the environmental impact of a product or service over its entire life cycle. This approach, commonly known as cradle-to-grave analysis, accounts for material extraction from nature, industrial material transformation, transportation, manufacturing and production, life usage, waste management and recycling [8]. To understand more about phases within LCA see table 2.1.

Phase	Considerations
Material extraction phase	Evaluate the environmental impact of extracting and delivering alumina. Provide insights into the sustainability of the initial material extraction processes.
Production phase	Assess the environmental impact of manufacturing processes. Consider energy consumption, emissions, and resource utilization during production.
Use phase	Analyze the environmental impact during the average lifespan of the product. Consider factors such as fuel consumption, energy use, and emissions during the operational life.
End-of-Life phase	Examine the environmental impact associated with the recycling and reuse of materials.

Table 2.1: The different phases of a Life Cycle Assessment

2.9 Noise, vibration, and harshness

Noise, vibration, and harshness (NVH) is one of the most important attributes for vehicle development. A vehicle with a good NVH behavior often results in much higher customer satisfaction by using a more stable vehicle. The NVH analysis will be focused on analysing all the battery tray as a pack and submitted under torsion and bending forces applied to both HFQ and HPDC concepts.

2.10 Weld types

The most common weld type is butt welding. This occurs when two metal pieces are placed next to each other and welded together in the same plane, unlike lap welds where the metal picec are laid on top of each other, see Figure 2.1.

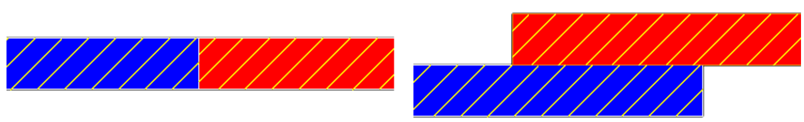


Figure 2.1: Image showing the difference between a butt weld (right) and a lap weld (left).

2.11 Friction Stir Welding

Also known as solid state welding where the heat generated is mainly by friction between the welding tool and the base material inducing a strong plastic deformation at low temperatures in comparison to other welding techniques. The heat zone produced is not as wide and does not generates fragile microstructure in the base material, one of the reasons to use this technique is because is faster and cleaner.

2.12 BEV batteries

The battery of a BEV consists of many small battery cells connected in series and parallel that together form the complete battery pack. These cells can be of different types: cylindrical, pouch, or prismatic are the most common ones[9].

Cylindrical battery cells consist of sheet-like anodes, separators, and cathodes that are sandwiched and rolled together into a cylinder. The disadvantage of having cylindrical cells in a BEV is the packing density. Due to their shape, there will be a lot of space between the cells when they are stacked together in a battery pack. However, this is an advantage with regards to cooling. The gap between the cells allows coolant to flow easily around them. Another advantage is the mechanical stability that their cylindrical shape offers. When the cells charge and discharge, and as they age, they swell and shrink, but the cylindrical outer shell can contain this swelling, causing the cells to remain the same size.

Pouch cells have no rigid enclosure; instead, they are sealed in flexible foil as cell containers. Due to their soft structure, a support structure is required to encompass the pouch. This support structure must take into consideration that the pouches undergo quite a bit of swelling; up to 10% swelling can occur during its lifetime.

Prismatic cells consist of large sheets of anodes, cathodes, and separators similar to cylindrical cells. The difference here is that they are pressed to fit in a metallic housing in a cubic form. This enables optimal use of space when combining multiple cells into a battery pack. This comes with a cost: the optimal space reduces cavities, which makes thermal management more challenging. Regarding swelling, the prismatic cells lie between the pouch cells and cylindrical cells. They swell a bit, but not as much as pouch cells. However, when stacking a lot of cells next to each other as you do in a battery pack, the swelling of each cell adds up, and quickly generate significant forces. This is a challenge that needs to be considered when designing a battery pack.

2.13 HPDC Footgarage Concept

The HPDC footgarage concept is the original concept that this master thesis study is trying to replicate using HFQ. The primary function of the HPDC footgarage is to offer rear passengers additional legroom. This is achieved by creating a volume or recess in the foot area, from now on referred to as the "tub", where passengers can comfortably place their feet. See figure 2.2 below.

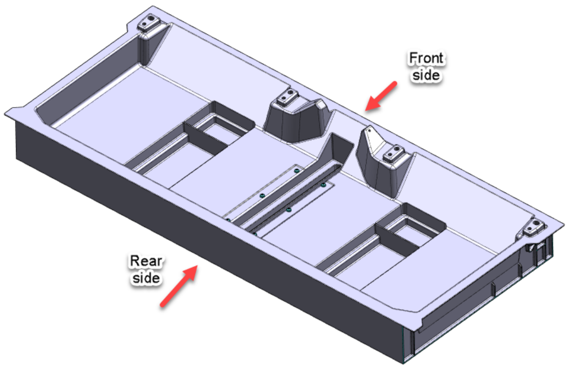


Figure 2.2: Image showing the original HPDC Concept. The front side of the footgarage is showing the seat mounting holes. The rear side shows only a side wall.

This tub itself serves multiple functions. It includes three support surfaces that connect the bottom of the tub to the bottom of the battery with strong adhesives. This is done to increase the battery's structural stability. Connecting the top shear plane of the battery with the bottom shear plane in as many places as possible improves the structural strength of the battery pack. The middle of these supports also acts as a safe channel for the battery's coolant lines that run from the front part of the battery to the rear. This channel is covered by a plate to protect the coolant lines against the feet of the rear passengers. The tub supports and the coolant line cover can be seen in Figure 2.3 below.

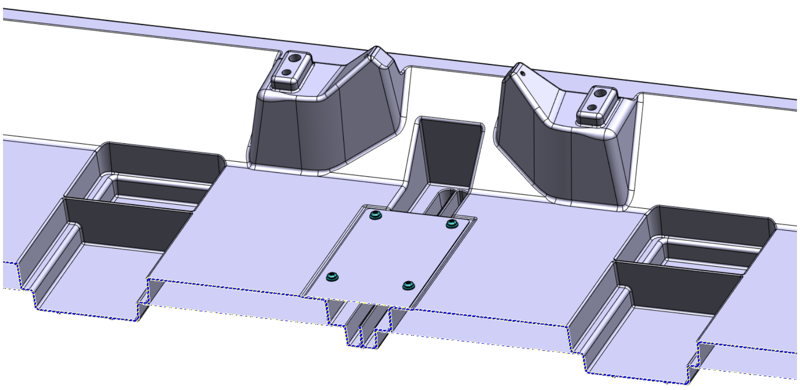


Figure 2.3: Cross section view of the HPDC tub supports. The middle tub support is covered by a cover plate to protect the cooling lines from the rear passengers feet.

The HPDC concept includes four seat attachment points with an M10 thread, one of the most important design requirements, see Figure 2.4. Adjacent to these threads are alignment holes used for mounting the seat, streamlining the alignment of the rails on which the seat sits during installation. These points in space are set by the seat department at Volvo Cars, meaning that they are stationary and cannot be moved.

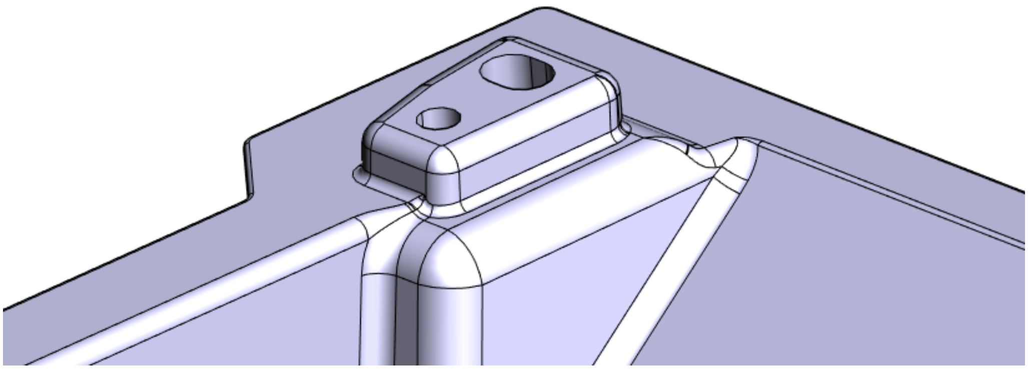


Figure 2.4: Left seat support attachment point. The large hole is the alignment hole for the seat attachment, and the small is an M10 thread.

Similar to the attachment points for the seat, there are also two points in space referencing M6 threads, see Figure 2.5. These serve as attachments to the car's center console. Unlike the seat attachment points, these points lack alignment holes. Instead, they feature two distinct planes/surfaces that guide the center console into the correct position during assembly. Just like the seat mount points, these points and planes are non-adjustable.

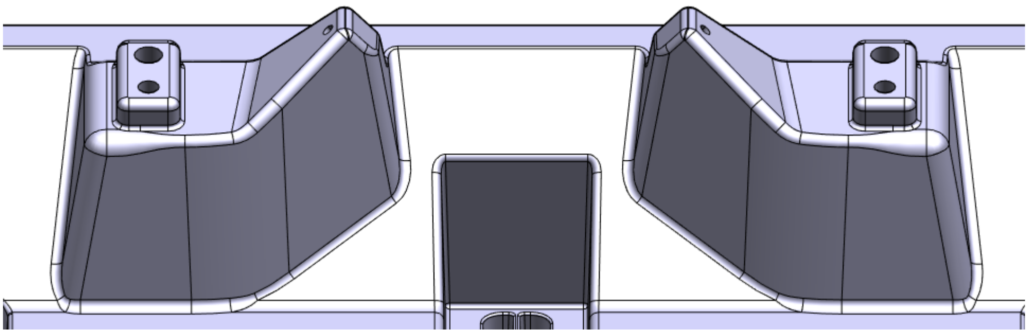


Figure 2.5: The two center console mounts. As can be seen the two M6 holes are located on slanting surfaces. Theses surfaces are there to self align the center console during the installation.

The HPDC concept also contains a somewhat non-obvious function. The front and rear sides of the foot garage acts as cell walls for the front and rear sections of the battery. Consequently, these walls must be vertical, flat, and capable of enclosing the battery cells while withstanding their swelling forces, see Figure 2.6.

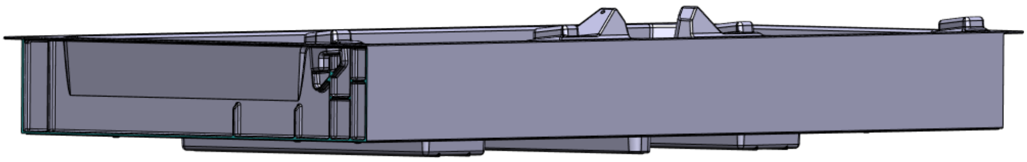


Figure 2.6: The front cell wall. The front and rear of the foot garage acts as the walls for the cells and thereby needs to be flat and vertical.

3
Methods

The methodology for this project was structured into three main phases with clear time frames: concept definition, concept refinement and concept evaluation. The task was considered to have a potential scope that was significantly larger than the project's time frames. This division was therefore made to ensure that a complete result would have been achieved by the end of the project. Even if all details were not resolved, there would still be a result that could provide an understanding of the use of HFQ technology in the footgarage.

3.1 First phase: Concept Definition

During the first phase of the project, the project's scope was defined to establish a clear foundation and direction for the development effort. The objective of phase one was stated as follows:

Develop an initial base concept of the footgarage, suitable for HFQ manufacturing.

Throughout the project, continuous contact was to be maintained with the company Impression Technologies (ITL), the creator of the HFQ manufacturing technique. The purpose of this collaboration was to ensure the development of a product that was well-suited for fabrication using the new technology. ITL's assistance was provided through expert advice and computer simulations demonstrating the behavior of sheet metal during the manufacturing process. To maximize the benefits of this support, a conceptual model was essential. This model served as a foundation for discussions and simulations. Consequently, the objective of phase one was to develop a concept model that could be refined through iteration into a final product.

3.1.1 Concept Definition Procedures

Research Study
Thorough research on HFQ technology, focusing on its design constraints and capabilities, was conducted. Understanding the design limitations of the technology was crucial for the success of the project. The goal here was to gather as much relevant information as possible.

Requirements Analysis
To clarify the development effort, a requirements analysis was conducted. In this

process, the requirements and desires for the foot garage were clearly defined. The purpose was to frame the work within the scope of achievable requirements and to guide the development toward meeting these desires. This requirements analysis was to culminate in a requirements specification, which was to serve as a guide throughout the development process and as a foundation for evaluating the project in phase three.

Design Initiation
The conceptualization of the foot garage and its integration within the vehicle was achieved using CAD tools and the requirements specification to create an initial model. The objective was to create a base model that will serve as a foundation for discussion and visualization. The rationale behind this approach is that an early concept allows more time for expert feedback and the iteration of the concept. The early concepts was also intended to serve as a source of inspiration for design ideas and problem-solving throughout the iterative process of refining the concept in phase two.

3.2 Second phase: Concept Refinement

In the second phase of the project the initial base concept was to be refined. The objective of phase two was stated as follows:

Refine the initial base HFQ concept of the footgarage to meet as many of the listed desires as possible.

The overall aim of the project was to create a concept that can pit the HFQ and the HPDC manufacturing methods against each other to be compared on a number of different criteria. In order for this comparison to be as accurate as possible, it is important that the HFQ concept meets as many of the requirements in the requirement specification as possible.

3.2.1 Concept Refinement Procedures

Collaboration with ITL
Throughout the refinement process, regular consultations and collaborations with ITL were conducted. This involved weekly design meetings where the latest design was discussed. In addition, the models were sent to ITL for simulations. These simulations identified weak spots in the design, places where the design could compromise the manufacturability of the part.

Volvo Cars Consultations
In addition to the simulations that ITL performed regarding the formability of the part, simulations were also conducted by Volvo Car's own CAE team. These simulations identified weaknesses in the design related to its structural integrity and NVH. The design was also discussed with material, welding, adhesive, ergonomic, standard parts and sustainability specialists to ensure that the HFQ concept was

integrated with the rest of the car in the best way possible.

Iterative Design Process
This second phase of the project followed an iterative process. Inputs from various simulations and experts were incorporated into the model as they were learned. Consultations with experts occurred repeatedly, uncovering new issues as the project progressed. This process persisted throughout the entirety of phase two.

3.3 Third phase: Concept Evaluation

In the final phase of the project the HFQ concept is compared against the HPDC concept.The objective of phase one was stated as follows:

Evaluate the the HFQ concept and assess the feasibility and effectiveness of using HFQ technology in its production.

In this phase an extensive A to B comparison between the HFQ and the HPDC concept were conducted across an assessment criteria established in phase one. The aim was to ascertain how effectively the HFQ technology could perform in applications such as a footgarage and similar components of a battery enclosure.

4

Results

In the following chapter, the results of the project's three different phases are presented.

4.1 Phase One

Phase one of the project generated four different documents and an initial model of the concept. The documents that were created were a Timeplan, Planning Report, Requirement Specification, and Assessment Criteria. The presented documents are included in the appendix.

4.1.1 Time plan

The first outcome of phase one was a timetable where all project-related activities were compiled, see appendix A. This timetable served as a time reference to identify and organize different activities such as documentation, presentation dates, meetings with experts, and relevant courses.

By roughly planning the project in advance, it ensured that the scope of the project did not grow to a disproportionate size. This promoted decision-making during the course of the project because all sub-steps had a predetermined time frame. This, in practice, put pressure on necessary boundaries and ensured that we stuck to our main task and did not focus too much on tangents.

4.1.2 Planning report

The planning report was one of the first task in the project. The purpose of the report was to deepen the understanding of the project at hand and to steer it in the right direction. The report outlines the project's objectives, background, tasks, and methodologies. The creation of the report led to a thorough consideration of the entire project as a whole. It effectively reduced the uncertainties of the project considerably by prompting light research on all relevant topics that were uncertain. The document referenced in this section is provided in appendix B.

4.1.3 Requirement Specification

The requirement specification document outlines both functional and technical requirements for the HFQ concept, see appendix C. The difference between these types of requirements lies in their focus: functional requirements specify what the system should do, while technical requirements detail how those functions should be implemented.

The HFQ concept is required to meet the same functional requirements as its predecessor, the HPDC concept, differing only in the manufacturing method. Functionally, it is supposed to serve as a key structural element in the battery pack, offer comfortable floor support for rear passengers, enclose the battery cells, include mounting points for essential components like the front seat and center console and integrate the coolant pipes for the battery's rear section appropriately.

Technically, the foot garage must comply with a variety of requirements. In the requirements specification, these technical requirements are divided into six different categories, see table 4.1. In the technical requirement specification some of the requirements are marked as wishes. Wishes are not necessary for the foot garage to be functional, but fulfilling the wish would enhance the performance of the foot garage.

Category	**Description**
Dimensional	Requirements related to size and measurements
Geometrical	Requirements concerning shape and form
User Needs	Requirements based on user preferences
Material	Requirements related to the type of materials to be used
Environmental	Requirements regarding environmental considerations
Features	Functionalities or attributes required

Table 4.1: A summary of the different categories that the technical requirements are divided into in the requirement specification document found in Appendix C.

The technical requirements outlined in the requirements specification served as guidelines in the construction of the design. These requirements were treated as goals or problems that needed to be addressed, while the wishes were used as a basis for decision-making. They allowed for determining which paths to take at crossroads during the design process. The path that likely fulfilled the most wishes was probably the one that achieved the highest performance for the foot garage and was therefore chosen as the path forward.

In addition to the functional and technical requirements, there are also several regulatory requirements. Regulatory requirements are standards or directives imposed by governing bodies or industry regulations that must be adhered to ensure compliance with legal or safety standards. These were not regarded as high priority considering the scope and duration of the project. Nevertheless, some were still utilized as guidelines, as they were deemed to align with good engineering practice.

4.1.4 Assessment criteria

The final document from phase one was the assessment criteria. This document was created to clearly define the criteria for comparing the HFQ and HPDC concepts in the final stage of the project, see appendix D. Seven distinct evaluation points have been meticulously outlined within the document. These points were crafted in a manner deemed suitable for the project's scope, established early on to guarantee an unbiased assessment of the concepts. They ensure that the evaluation remains focused on criteria essential to the project's objectives. A summary of the developed assessment points can be seen in table 4.2.

Assessment Points	**Description**
Function Performance	Functional requirements and technical desires.
Sustainability	Mainly focused on CO_2 impact.
Part Price	An estimation of concept price.
Investment Cost	Estimation of investment cost of HFQ.
Manufacturing process impacts	Main impacts to the manufacturing process.
Time to Market	The time each concept take to implement.
Material Base	Possible alloy selections.

Table 4.2: A summary of the outlined assessment criteria from the assessment criteria document found in appendix D.

4.1.5 Concept Design

The final output from phase one was an initial model of the HFQ concept, which served as the foundation for further development in phase two. This model underwent several revisions with the aim of creating a one-to-one representation of the HPDC concept in sheet metal. The objective was to closely mirror the HPDC concept while ensuring geometric feasibility for a sheet metal design. Each property was meticulously implemented until the replica was finalized.

4.1.5.1 Initial HFQ concept creating process

The second revision of the initial HFQ concept was the first solid model of the concept, and it already included some essential features extracted from the pre-study of the footgarage, as shown in Figure 4.1. It featured a dedicated tub for passengers feet, with simple seat attachments to the front seats. Supports connecting the tub to the battery floor, or under tray as its called, were incorporated in a similar way as the HPDC concept. Furthermore, 90-degree flanges were modeled on the front and rear of the tub to serve as cell walls for the front and rear cell compartments of the battery.

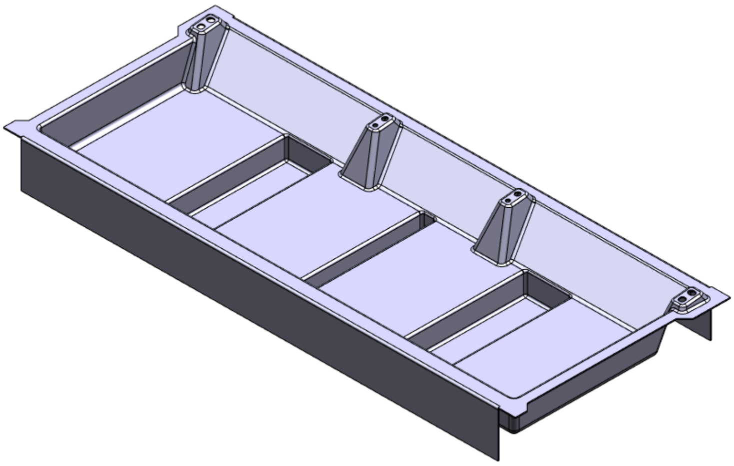


Figure 4.1: Initial HFQ concept revision 2: The first solid model of the initial HFQ concept.

In the subsequent revision (revision three) of the initial HFQ concept, seen in figure 4.2, the inner front and rear walls of the footgarage were merged with the front and rear sides of the tub supports, forming one continuous wall. This change was implemented to simplify the geometric complexity. It was not expected to impact the functionality of the foot garage.

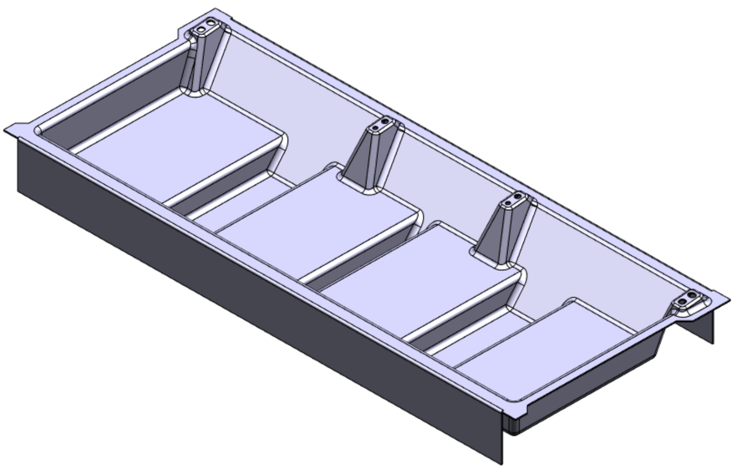


Figure 4.2: Initial HFQ concept revision 3: Tub- and tubsupport walls merged into one continuous wall to reduce geometrical complexity.

The next revision (revision four) shown in figure 4.3, included two core features of the footgarage: the center console mount and a channel for the coolant lines leading to the rear of the battery. These features posed significant challenges in sheet metal reproduction, and it became evident early in the process that a lot of effort in this area would be needed to develop a manufacturable design.

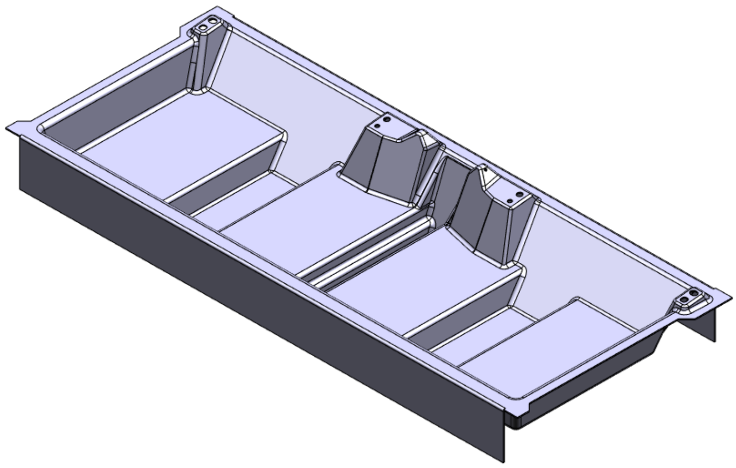


Figure 4.3: Initial HFQ concept revision 4: Introduction of the center console mount and the coolant line channel leading to the rear of the part of the battery.

The design change in the next revision (revision five) targeted the center console mount with an update. Acknowledging the formability challenges in this area, the focus was on minimizing the steep draft angles and tight radii to mitigate potential issues. As illustrated in figure 4.4 below, additional surfaces were incorporated in an effort to address this concern.

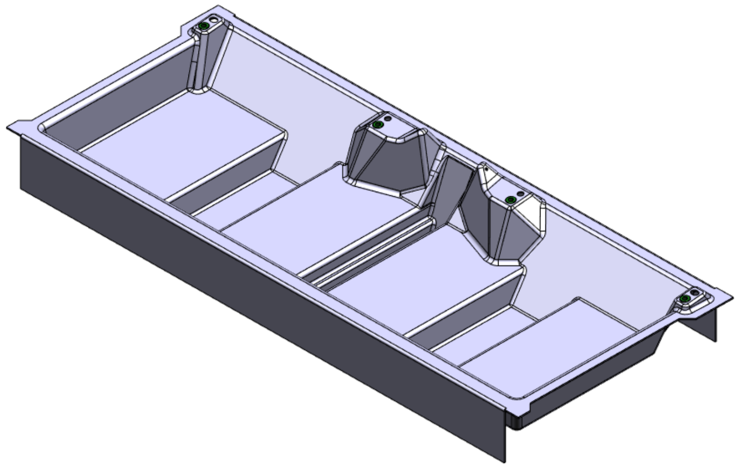


Figure 4.4: Initial HFQ concept revision 5: Center console mount update. Radii, draft angles and surfaces have been added to adress concerns regarding the formability of this area.

The fifth revision underwent thorough review by specialists at ITL. After closely examining the model, they provided a comprehensive report suggesting design changes aimed at enhancing formability. The primary areas of concern highlighted by the experts were corners, radii, and draft angles. While adjustments to corners and draft angles were relatively straightforward, the recommended changes to radii posed challenges in certain areas, notably the center console mount and coolant channel.

To accommodate ITL's recommendations, a redesign of these sections was necessary, incorporating their suggestions from the ground up. The resulting design, depicted in Figure 4.5 below, reflects these modifications. Additionally, a final feature was added to the foot garage: a protective plate covering the coolant channel to shield the coolant lines from the feet of rear passengers.

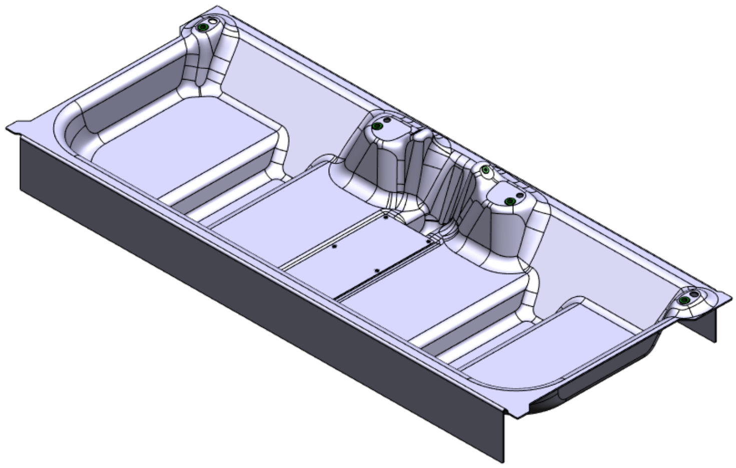


Figure 4.5: Initial HFQ concept revision 8: Major updates were carried out according to ITL's recommendations. Mainly, draft angles, radii, and corners were increased. Additionally, a cover plate for the coolant lines was implemented.

After incorporating all recommendations from ITL and modeling the coolant pipes, the initial HFQ concept was now considered complete, and henceforth referred to simply as the HFQ concept. Theoretically, the design fulfilled all functional requirements. However, to validate this and address any potential issues, extensive simulations and analyses by experts were required, along with numerous iterations of the model. With this achievement, phase two could commence.

4.2 Second phase

In the following section, the second phase of the project is described. During this phase, the initial base models were further developed and refined into a final concept. The phase consisted of continuous feedback from specialists. The HFQ concept was simulated and discussed with experts, undergoing many updates based on these interactions. The key information received from these various specialists is described separately below. However, in reality, all these interactions took place simultaneously, meaning that an update to the HFQ concept could have been influenced by feedback from several different types of experts.

4.2.1 CAE experts

The team initiated meetings with CAE due to concerns about the seat attachments and the seat rails that might not be strong enough in case of a crash scenario. Crash data from previous tests in similar vehicles were obtained for the safety department at Volvo Cars. The forces estimated on the seat attachment were 22,8kN at the central seat attachment. This information was then transferred to the battery CAE team, which simulated the deformation of the foot garage with those forces realising that the deformation was under control. There was some local plastic deformation around the rivet nuts and around 3mm of elastic deformation around the middle of the foot garage. While this might sound significant, since the rest of the vehicle would be completely damaged, it fell within safety standards.

During the meetings, the team also had the opportunity to discuss the overall design they had come up with. An issue with the design was immediately spotted by the CAE experts. As previously stated, the front and rear walls of the foot garage acts as containing walls for the battery cells. In the design, these walls were implemented in the form of two sheet metal flanges that were bent to 90 degrees in the front and rear of the foot garage. The CAE expert pointed out that these flanges were not strong enough to support the swelling forces the battery cells generates as they age. These swelling forces were known, but they had been severely underestimated. It turned out that these forces were estimated by the CAE team to be around 200-300kN spread across the cell wall, far to large for the sheet metal flanges to handle. This was a major flaw in the design, and a redesign had to be made.

In the redesign, the flanges were completely removed and replaced them with two cross members, see figure 4.6 below. This change increased the overall weight of the concept, but it was deemed a necessary step to counteract the swelling forces. As was later found out, it also helped with the overall rigidity of the battery, crash performance, and the welding process.

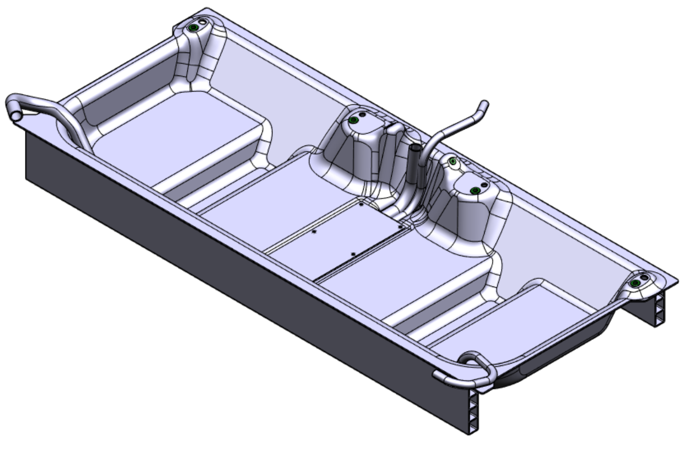


Figure 4.6: Image showing the two crossmembers that replaced the sheetmetal flanges used as cellwalls in the battery pack.

This change inspired another concept alteration. The footgarage sheet metal front and rear edges now aligned roughly with the battery's front and rear lids. Combining these three parts into one single part was now a possibility. Not only would it reduce the complexity of the battery by decreasing the number of parts, but it would also enhance the battery's seal. Creating the entire lid as a single part would simplify the welding process by reducing the number of welds that need to intersect. With a single uninterrupted contour FSW weld line sealing the battery, the repeatability of the battery seal would increase. See figure 4.7 below.

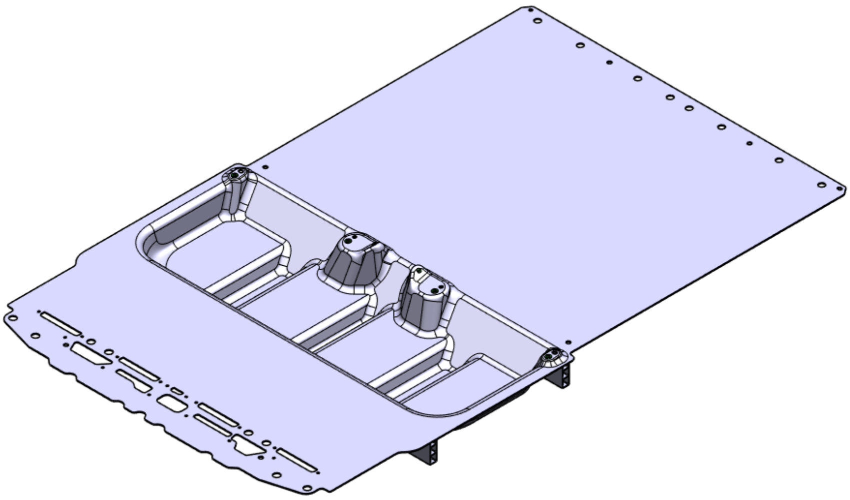


Figure 4.7: Figure illustrating the concept of combining the battery packs front and rear lids into one part.

Unfortunately, this proved to be impossible for now. As part of the HFQ process, the sheet metal blanks have to be heated to their solution heat treatment temperature in an oven before they are stamped. At the time of the project, ITL did not have an oven large enough for such a large part, and therefore the idea was scrapped in order to keep the project within reasonable terms. However, in theory, this is possible, provided that a larger oven could be used.

4.2.2 Welding experts

The meeting with the welding experts provided valuable information that influenced the design of the foot garage. Battery cells release gases as they age, which are not healthy for humans to breathe. Therefore, all welds on the battery, situated at the boundary between the inside and outside of the battery and in close proximity to humans (the interior, in other words), must meet a very high standard for gas leakage. The required tightness that Volvo Cars safety department has set is similar to an IP67 rating.

A solid weld that can provide sufficient gas protection can be achieved with many different welding techniques. The issue lies in repeatability, since the volume of car welds in a manufacturing line is enormous, the weld needs to be foolproof. That is why all sealing welds located in the car's interior is recommended to be of the FSW type. The FSW is a type of weld with good sealing properties and a high repeatability. Since the footgarage serves as a direct barrier between the battery's interior and the car's interior, this recommendation also applies to the footgarage.

The experts also provided information regarding the forces exerted on the part during the welding process. These forces measure around 15 kN. Consequently, when welding two components together, they must either withstand this point force or utilize a support to counteract it. In the context of the foot garage, this implies that both the side beams and the cross members must possess sufficient strength to endure 15 kN at the weld lines.

During the meetings with the welding expert, valuable insights were gained into the necessary clearances that the FSW process requires. The key information gained included the space needed for the FSW tool head to reach the weld lines, the width of the weld itself along with the required margin and the alignment tolerances of the parts to be welded. Beyond this, various types of welding solutions regarding the positioning of the parts were discussed during the meetings, such as butt welds, lap welds, or crossings of welds, for instance.

With a greater understanding of the FSW process, the concept received more updates. It became clear that the margins had to be adjusted since they were previously too narrow to accommodate the correct tool width. The previously scrapped idea of having one complete lid now resurfaced but in a slightly altered fashion. This time, the three different parts - front lid, foot garage, and rear lid - will be butt-welded together, forming one complete lid. This complete lid will then sealed with a continuous contour FSW weld. See Figure 4.8

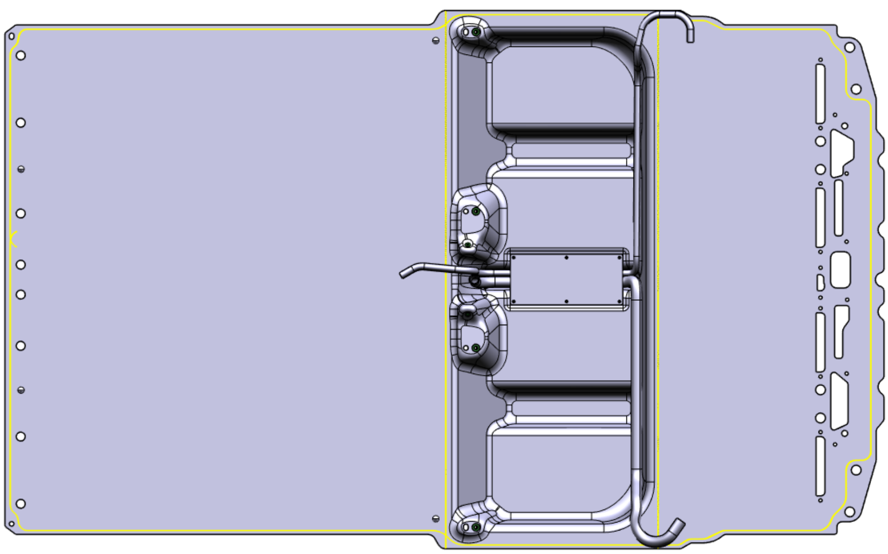


Figure 4.8: Image showing the weld concept. Note the weld lines in yellow and the increased margins around the footgarage welds.

The difference here compared to the original HPDC concept is the butt weld. In the HPDC concept, the three pieces are welded together using lap welds. The switch to butt welds in the HFQ concept accomplishes two things. Firstly, it removes the need for machining out a shelf in the side beams for the HPDC footgarage to rest upon. This machined shelf was required to position the foot garage at the proper height for the lap weld. Secondly, it simplifies the welding process. The contour welding in the HFQ concept can now be made completely with FSW in one singular plane, due to the cross-welded properties of FSW. This simplifies an issue regarding contour welds on the HPDC concept around the lap welding area by reducing the risk of leakage.

4.2.3 Forming Experts

The formability of the HFQ footgarage's tub proved to be a difficult task that spanned the entirety of the second phase. During this phase, a number of forming simulations and discussions were held with the forming experts at ITL. The forming simulations could determine the amount of sheet metal thinning at any given region of the tub. This data was provided during the weekly meetings, and potential changes that could reduce the thinning were discussed. According to ITL, the maximum allowed thinning is 20%. In the initial simulations, some parts of the footgarage had a thinning of around 90%, significantly exceeding the target. These areas of the tub naturally became the focus of the development efforts and are showcased the remainder of this section.

4.2.3.1 Center tower

The center tower of the foot garage is the mounting point for the front seats and the center console. Due to this fact, the points in space where these mounts are located are fixed. This poses difficult demands regarding the formability of the center tower. The main issue is its draw depth and location. A large draw depth means that the overall footprint of the feature increases due to the draft angles, which also have to be larger when the draw depth is increased to now cause cracking. In this case, a larger footprint means less feet area in the foot garage, which is not desirable. Below in Figure 4.9, some of the different revisions are showcased in chronological order of release.

As can be seen, the early center tower consists of two separate towers that are relatively small, while the later ones form a large connected tower. The main changes that had to be made were to increase knuckle size, draft angle, radii, and to connect the towers into one. All of these changes reduced the feet area of the foot garage, either by increasing the footprint of the center tower or, as in the connecting of the towers, pushing the coolant line channel backward, causing the coolant lines to protrude into the foot garage volume. This decrease in footgarage volume is not desirable, but it's a necessary tradeoff to achieve a formable footgarage.

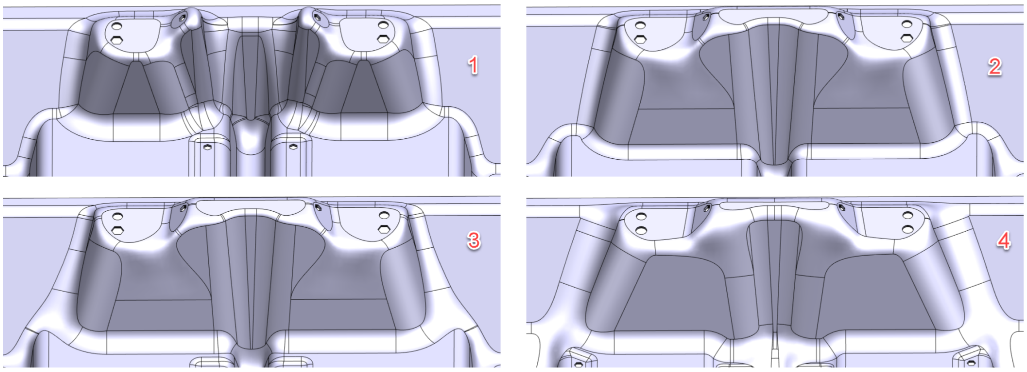


Figure 4.9: Image depicting some of the revisions of the center tower. Notice how the overall size increased as the iterations moved towards a more fromable design.

4.2.3.2 Seat Mount

The left seat mount was not as difficult as the center tower, but it did not come without its issues. First of all, the initial concept developed in phase one did not have enough margins around the attachment itself. This means that the FSW does not have enough space and cannot be performed correctly. Secondly, the mount itself had too sharp corners in combination with deep draw depth, which caused too much thinning to occur. These issues were solved through a series of trial and error, during which the mount underwent a smoothing process. See some of the revisions in Figure 4.10 below.

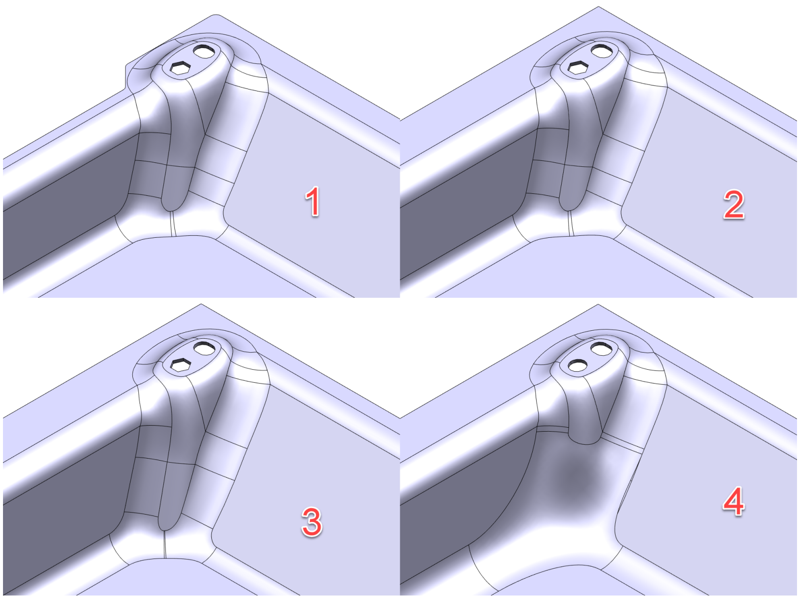


Figure 4.10: Image of some of the revisions of the left seat mount. Notice how the dept of the tub increased between image two and three.

4.2.3.3 Coolant Line Channel

The coolant line channel, or the center tub support, proved to be one of the most difficult parts to form. It is positioned in the center of the foot garage tub at its deepest point. The position of this feature makes it difficult to form because the surrounding material is already formed, meaning that there is less material to draw from. Another difficulty arises from the channel's minimum and maximum widths, which are very close to each other, limiting design freedom. Additionally, steep draft angles are necessary due to the surrounding geometry. Many revisions were made to reduce the amount of thinning to manageable levels. Some of these revisions can be seen in the Figure 4.11 below.

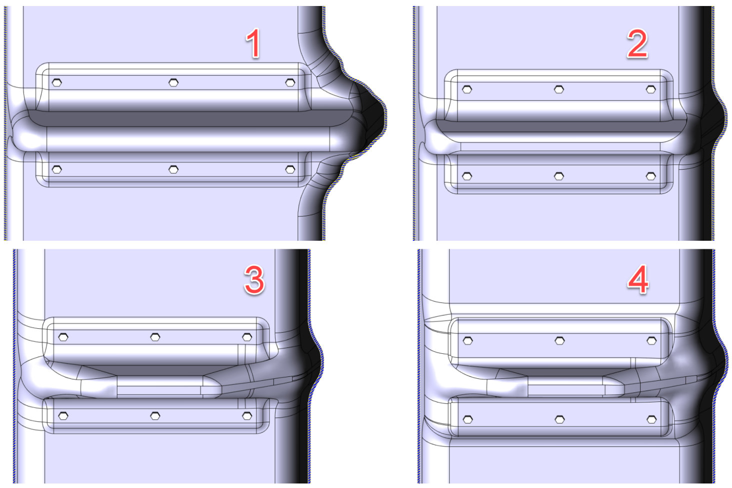


Figure 4.11: Image showing four revisions of the coolant line channel. The major changes include lowering of the floor, addition of slants at the beginning and end of the channel, and another local lowering of the floor.

As can be seen, the final revision of the coolant channel is a lot smaller than the first one. It is both shorter and shallower. Due to the formability issues around this area, one of the necessary steps taken in problem-solving was to lower the entire floor of the foot garage by 15mm. This reduced the local draw depth of the feature, but on its own, it was not enough. Where the channels transition into the front and rear walls of the foot garage, the largest draw depth of the entire tub is located, which is causing a lot of thinning. This is why slanted surfaces were incorporated to smooth out the transition from walls to floor and reduce thinning in those areas.

Despite these attempts to gain control over the thinning, it was not sufficient and further changes were needed. What was done was to lower the area around the coolant channel, effectively creating an additional local lowering of the floor. This adjustment solved the issue, but now the coolant lines did not fit in the channel and would protrude out on top. A custom cover plate was now necessary to protect the coolant lines from the rear passengers' feet. Though not ideal, it was a necessary step for the HFQ concept.

4.2.3.4 Tub support

The left and right tub supports also underwent a lot of changes during the second phase, even though most efforts and difficulties were focused on the central features of the footgarage. Initially, large amounts of thinning occurred on the steep walls and in the tight corners. Two of the main solutions to address the tub supports forming issues were to lower the floor by 15mm and to reduce the length of the supports by creating a bend in the front and rear of the tub support. In addition to these solutions, draft angles, radii, and knuckles were used to minimize the amount of thinning. In Figure 4.12 below, some of the revisions of the tub supports are showcased.

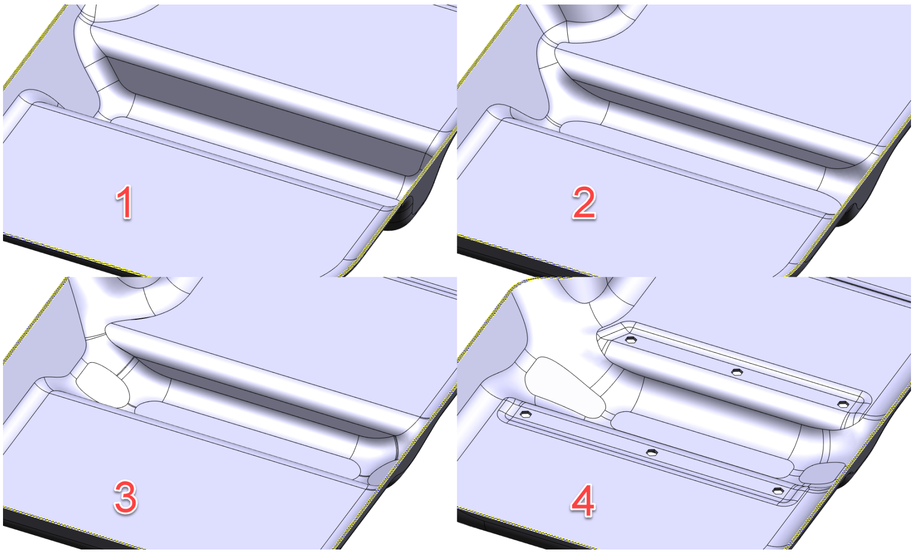


Figure 4.12: Image depicting some of the revisions of the tub supports. Notice how the depth and length are decreasing as the supports take on a more formable shape.

4.2.4 Ergonomic

During phase two, a discussion with the ergonomic department was also conducted. Vital information for the success of the footgarage concept was obtained from this interaction as well. Through these discussions, the key variables that could have a significant impact the ergonomic were identified.

Typically, when a rear passenger enters a BEV, they place their feet on top of the battery. For a car with a footgarage, the passenger has to step over the edge of the car's battery and place their feet inside the foot garage when entering the car. This battery edge is, in reality, a structural beam that provides structure to the entire car and is a vital part of crash absorption. Due to these facts, the side beams tend to be wide, thus the battery's edge will be wide, and the step-in distance will be longer. In Figure 4.13 below, you can see how the distance from the side beam to the floor is measured. Notice the space between the inside of the side beam and the actual feet area that is caused by the draft angle and edge radius of the HFQ concept.

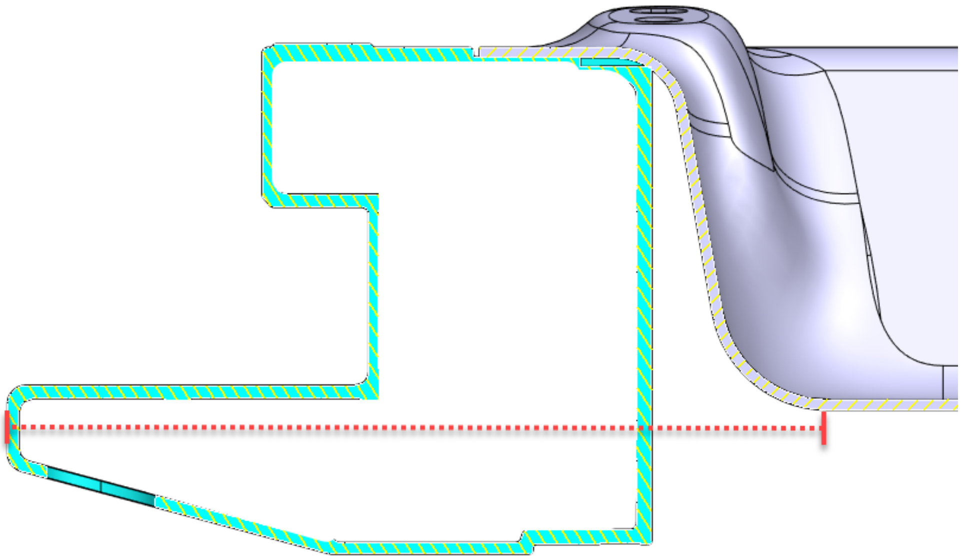


Figure 4.13: A visualisation of how the step-in distance is measured. Note that the insides of the beam is hidden.

Similar to the step-in distance, there exists a seat-to-heel distance that is an important factor of the rear passengers comfort. The ergonomic specialist wants this distance to be as short as possible for increased comfort. But due to similar reasons as for the step-in distance, the battery layout limits the design freedom here aswell. Specifically its the cells of the rear compartments that needs to be considered.

In the HPDC concept, the step-in distance and the seat-to-heel position were both on the verge of what could be classified as good due to the side beam and cell layout. And since the HFQ footgarage concept requires draft angles and radii to be formable, these distances will increase. This is of course not good, but its unavoidable. Unfortunately no optimisation of the draft angles and radii were possible due to time limitation.

Tied to these discussions with the ergonomic team at Volvo Cars was a conversation with a carpet expert. From this conversation, an understanding of what could be accomplished with the interior carpet design emerged. New sustainable carpets made out of a single felt-like material are planned for the future. Unlike the old carpets, where foam and carpet fabrics were combined to shape the carpet to the required geometry, the felt carpet has a variable thickness between 9 mm and 20 mm. This implies that the underlying surface has to be close to the final shape of the car's interior floor. Due to this knowledge, two covers were implemented to cover the tub's side supports and provide a surface for the carpet to lie on.

4.2.5 NVH

The NVH expert, who had also worked with NVH simulations on the HPDC foot garage, pointed out some important aspects regarding NVH of a footgarage. The first one was that large corner radii benefits NVH simulations and having several big radii covering big part of the component is an advantage since the corners had been shown to be a week spot on the HPDC concept. In comparison to the HFQ concept, the casted concept provides more structural support and stability to the battery tray due to its rectangular shape, mass and volume, which is not the case for the HFQ concept since it is produce entirely in sheet metal lacking front and rear structural support. Therefore, it was necessary to design new support beams and install them on the front and rear side of the HFQ footgarage to provide more contact surface support to increase the stability of the new concept. The main purpose of the support beams or crossmember beams is to contain the swelling forces from the battery cell, and it was necessary to change their shape to provide more joining surfaces and improve the connections between the top and bottom sheer planes which in turn would reduce static bending and static torsion.

4.2.6 Standard Parts experts

Thus far in the development process, a total of 24 rivet nuts have been utilized in the assembly. Four of these are M10 rivet nuts, intended for mounting the front seat attachments. Two are M6 and will serve as mounting points for the center console atop the footgarage center tower. The remaining 18 rivet nuts are designated for securing the three cover plates on the floor. As advised by the standard parts experts, rivet nuts are relatively expensive and should be substituted with other alternatives whenever possible.

The two side cover plates do not conceal anything; their sole purpose is to provide a surface for the carpet. Therefore, the ability to remove these cover plates is unnecessary, allowing them to be spot-welded or glued in place, which is a cheaper alternatives.

The center cover plates must be removable, as they cover the coolant pipes that might need replacement or repair. While speaking with the standard parts experts, an interesting suggestion emerged. The experts noticed a potential solution for mounting the cover plate that could also serve as a mounting solution for the carpet lying on top of the plate. They suggested a multipurpose stud developed for similar purposes. The recommended stud could mount the plate while simultaneously attaching to the carpet, a good solution that was adopted in the design.

During the meetings, the sealing properties of the remaining 6 rivet nuts were discussed. Since the rivet nuts will be part of the barrier between the inside and outside of the battery, they have to seal properly. More specifically, they need to have an IP67 rating, which means they must be completely dustproof and withstand 30 minutes of submersion in water at a depth of 1 meter. According to the experts, these types of rivet nuts exist in the M6 size but not in the M10 size required for the seat attachments. However, they mentioned that M10 rivet nuts with sealing properties are currently under development. This was good news, and it was concluded that the rivet nuts under development could be used in the case of the HFQ foot garage.

4.2.7 Adhesive experts

Adhesives provide extra stability to the structure, which is why they were applied underneath the original HPDC concept to provide extra structural support by connecting it to the undershield, the same applies to the HFQ concept. After consulting with the adhesive expert, it was determined that the glue stripes are a good and easy solution to provide structural support ideally recommended thickness between 1mm to 3mm.

There are other parts inside the battery tray where the thickness of the glue exceeds that range. However, an important trade-off to consider is that the thinner the glue stripe, the more structural it behaves. On the contrary, thicker glue stripes offer a better NVH response. Since is not the footgarage tub that provides a better NVH by itself, is the parts attached to it that provides must provide strength and stability, for instance, a good NVH behaviour by applying a glue thickness of 1 mm.

The recommended adhesive to apply for the HFQ concept is polyurethane since is the better solution for NVH purposes, provides flexibility when bonding different materials, and does not need laser treatment and will be applied to some areas between the HFQ footgarage and the undershield: between the tub and the cross-member beams, between the tub and the cover plates, and between the tub and the undershield. Figure 4.14 show the exact position where the glue strips are located one the footgarage tub.

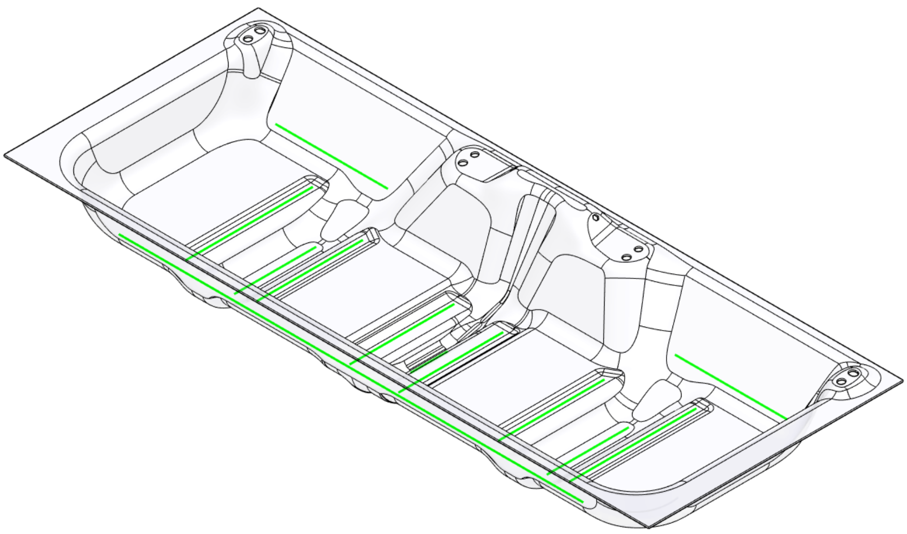


Figure 4.14: Image depicting the adhesive locations on the HFQ concept.

4.2.8 Crossmember Beams

After the realisation that the original flanges intended as cell walls were way to weak a new investigation on crossmembers started. At first, a crossmember design of another battery variant was considered to be carried over to the HFQ concept. This seemed to be a good option since the beam was already designed and simulated for this kind of purpose. However, the NVH experts suggested the designing of a beam that could facilitate joining area to the footgarage tub's front and rear. This would strengthen the HFQ concept's static bending and static torsion and therefore increse the NVH performance of the concept. This started the design process of a custom crossmember for the HFQ concept.

To proceed with the design, it was necessary to define the functional requirements or loads that each beam will be affected before and after the final assembly into the battery tray. These can be seen in table 4.3 below.

Crossmember functional requirements.
Support the swelling forces from both rear and front side.
Provide contact area for the use of adhesives.
Provide support and stability to the foot garage and assembly.
Support the forces from the different welding processes.
The beams should be as light as possible.

Table 4.3: Functional requirements of the crossmembers.

The following Figure 4.15 shows the technical requirements for the design of one of the crossbeams.

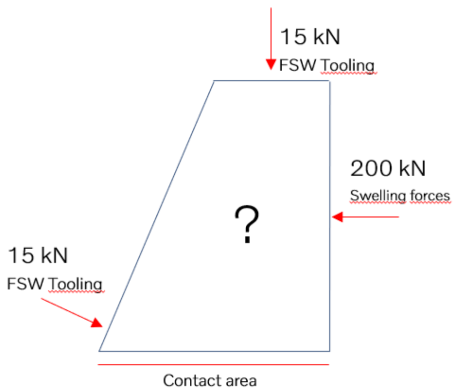


Figure 4.15: Initial forces requirements for the development of the crossmember beams. These requirements were changed while the development was moving forward.

After gathering the forces that the crossmember had to withstand to meet the functional requirements, Volvo´s CAE experts performed a simulation on the initial concepts and their first proposal is visible in Figure 4.16. The first proposal for the design was considering extending the beams to the undershield but this implied more weight and modifying nearby elements that could increase the price of the overall concept.

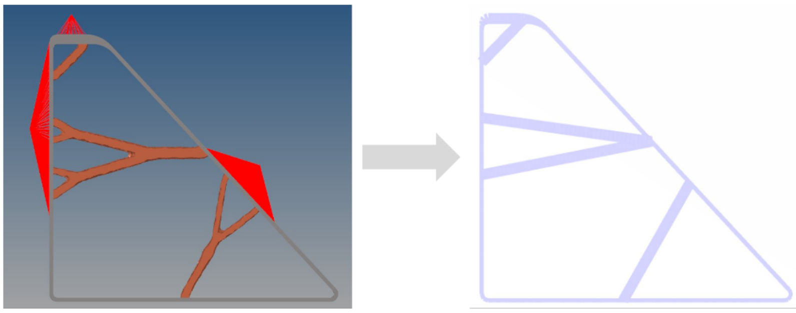


Figure 4.16: Crossmember optimization analysis

The results from the simulations indicated the need to add ribs inside the beam for internal stability, however, this increased its weight unnecessarily, and some sections weren't effectively used for force containment. Moreover, extending the beam to the undershield would require changes to nearby components, like a component called the carrier located between the foot garage and undershield, potentially affecting its function and demanding extra cut-outs. These alterations could raise manufacturing costs and making the assembly more complex. Following recommendations from CAE on force distribution and weight reduction, along with input from the R&D battery department on pricing and manufacturing, the cross beams were redesigned with inner ribs and new shapes for a more streamlined setup. Finally, it comes to the final shape shown in Figure 4.17 where both crossmembers are located to support the HFQ footgarage tub.

Figure 4.17: Frontal and Rear crossmembers supporting the HFQ footgarage tub.

At this point of the crossbeam development, the glue expert expressed his worries regarding the incline surfaces that touches the foot garage. It was thought that some adhesives or glue will be applied in those surfaces but in order to increase its gluing effect and to provide more structural support, it was recommended to apply laser treatment in the areas where the glue will be applied and use a specific type of glue called polyurethane adhesive. In addition, according to his recommendations, some glue "bumps" will be necessary to add in the design so the glue can be contained and provide a spacing of 1mm in between both parts. The bumps height is 1mm and 2,5mm wide and it is visible in Figure 4.18.

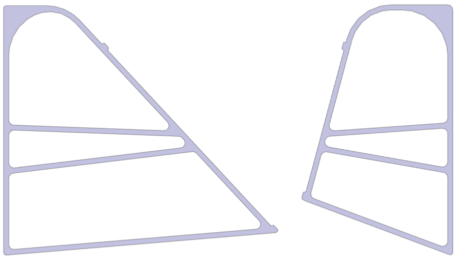


Figure 4.18: Closer look of the final rear crossmember. Notice the glue bumps on the slanted surfaces.

Finally, after considering an extra CAE analysis considering the higher forces applied in one of the beams, the swelling forces from the battery cells which are 200 kN applied on the vertical wall, the final deformations where just only 0,3mm in the x-direction which it seems the design is strong, see Figure 4.19.

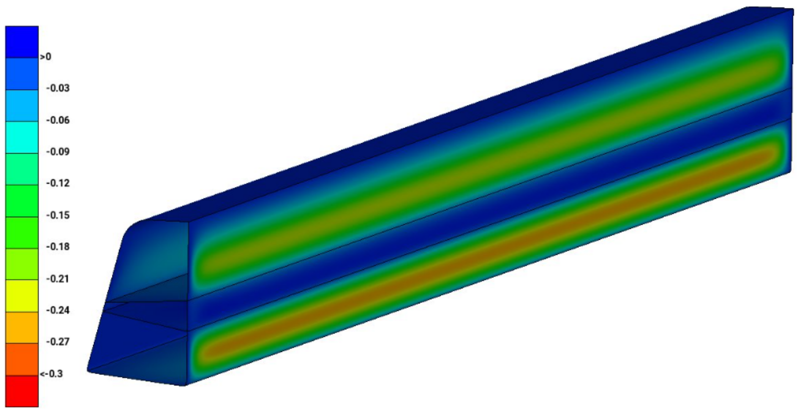


Figure 4.19: Crossmember beam deformation simulation.

Lastly, Figure 4.20 shows the development process for the crossmember where the changes and optimization are very visible.

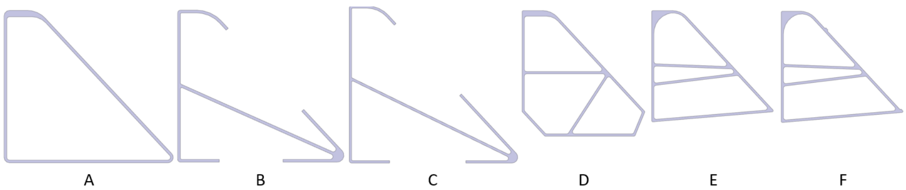


Figure 4.20: Final crossmember development process

4.2.9 The Final HFQ concept

Once phase two had come to an end, the design of the HFQ was frozen to create time for the last phase of the project, the evaluation. This final freeze can be seen as the outcome of phase two. It is the HFQ concept that this project came up with. The final HFQ concept can be seen in figure 4.21 below.

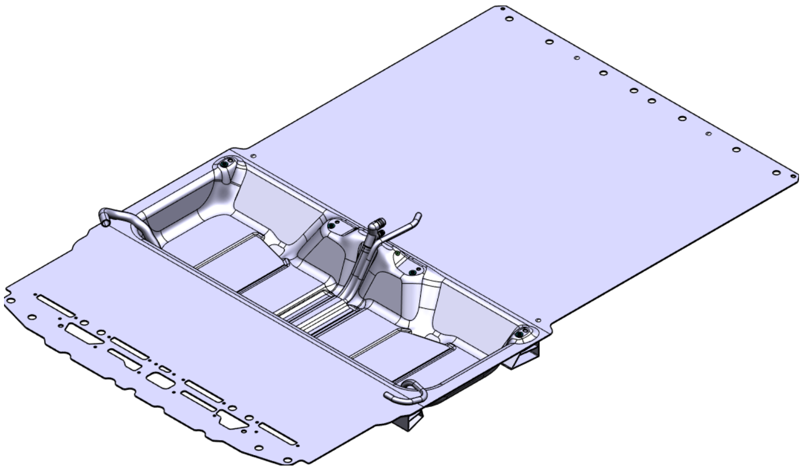


Figure 4.21: Final HFQ concept.

The final HFQ concept consists of six rivet nuts for the seat rails, one foot garage tub, a front lid, a rear lid, three cover plates, and two custom crossmembers. As can be seen in Figure 4.22 below, the final HFQ concept achieves a thinning of less than 20%. In other words, it is formable.

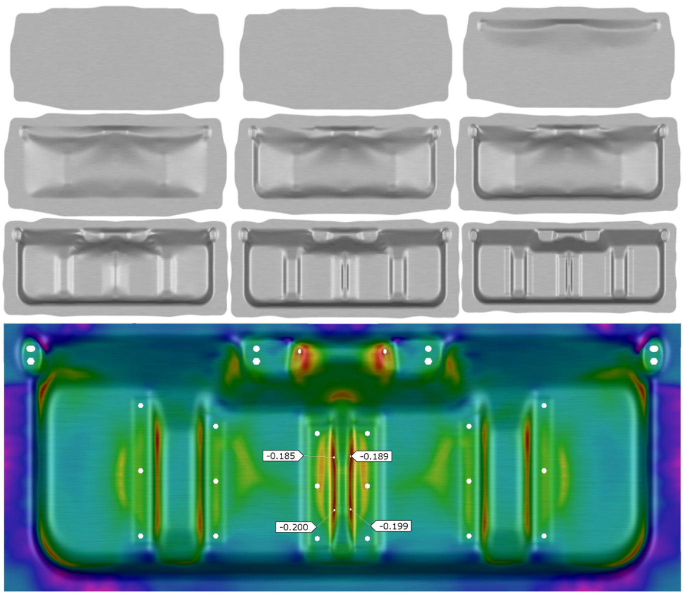


Figure 4.22: Thinning analysis for formability. If the thinning is under or equal to 20%, then formability is confirmed. The forming process starts from the top left corner and finishes at the bottom right corner.

4.3 Third phase

In the third phase of the project, the resulting HFQ concept from the first two phases is evaluated. It is compared to the original HPDC footgarage concept on the seven different aspects developed in phase one of the project. Each of the different assessment criteria is discussed separately below before an overall assessment is done at the end of this section. The two concept that are to be compared against each other can be seen in Figure 4.23 below.

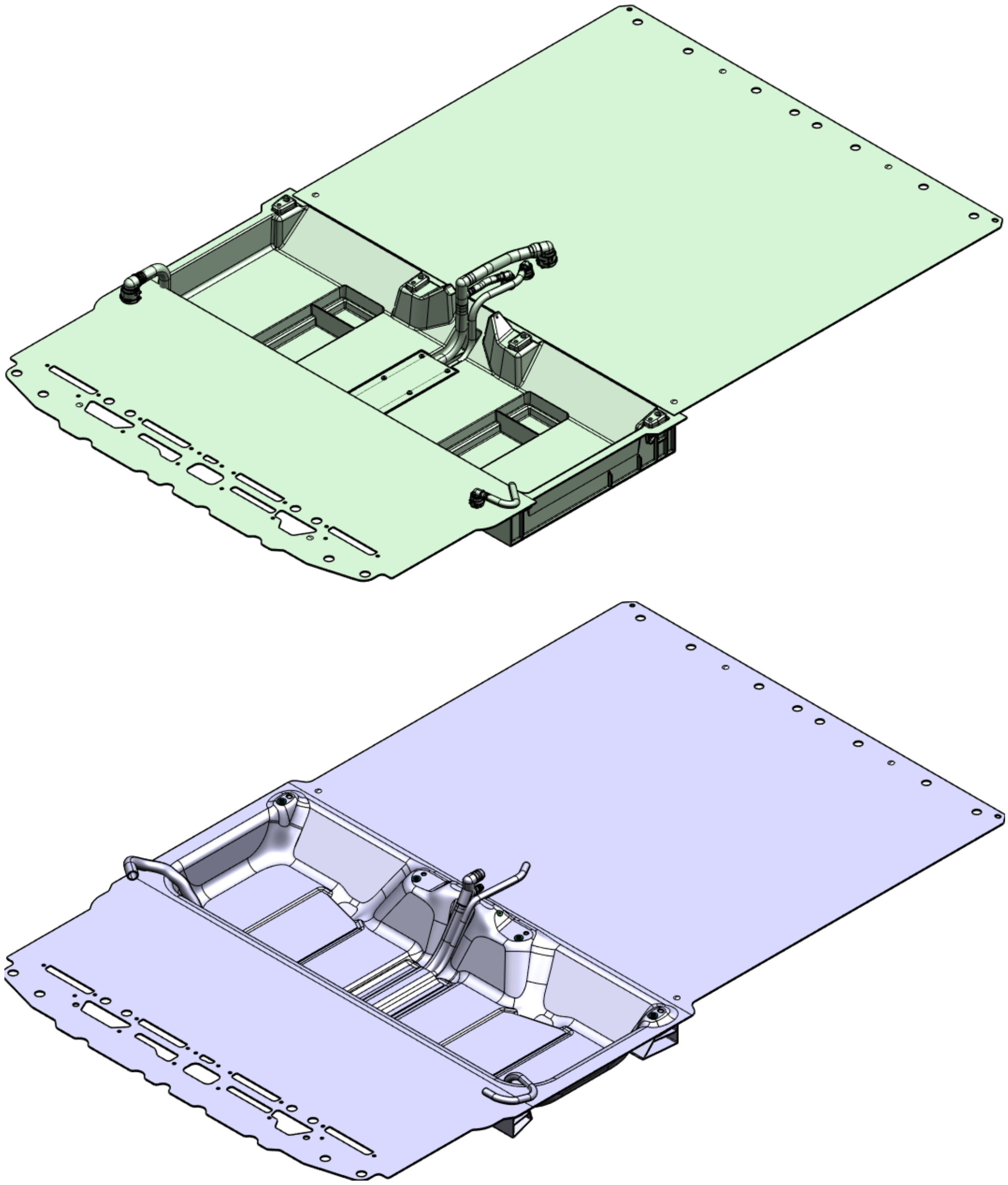


Figure 4.23: The image shows the two different concepts being compared. At the top is the HPDC concept, and below is the HFQ concept.

4.3.1 Function Performance

In the assessment criteria document created during phase one of the project, the functional performance assessment criteria are defined as follows:

The function performance is evaluated by assessing how well the functional requirements are met. The evaluation will consider the necessary steps taken to fulfill the functional requirements in both concepts. It will also compare the degree to which the desires in the requirement list are fulfilled, which will act as an objective value of performance

The functional requirements in the requirement specification document is separated into six different categories, each discussed separately below.

4.3.1.1 Dimensional requirement evaluation

The dimensional requirement describes the allocated space within which the footgarage is allowed to occupy. All of the requirements are met in this category, and there are no clashes with other parts in the HFQ concept.

4.3.1.2 Geometrical requirement evaluation

The geometrical requirements describe all the unique geometries that the footgarage must meet. In this category, there was one uncertain requirement. This requirement specified that the coolant pipes must be protected from the rear passengers' feet. The HFQ concept, like the HPDC concept, implemented a cover plate for the coolant pipes in the floor. However, in the HFQ concept, the geometry of the center tower forces the vertical part of the coolant pipes further back towards the feet of the passenger, as shown in Figure 4.24 below.

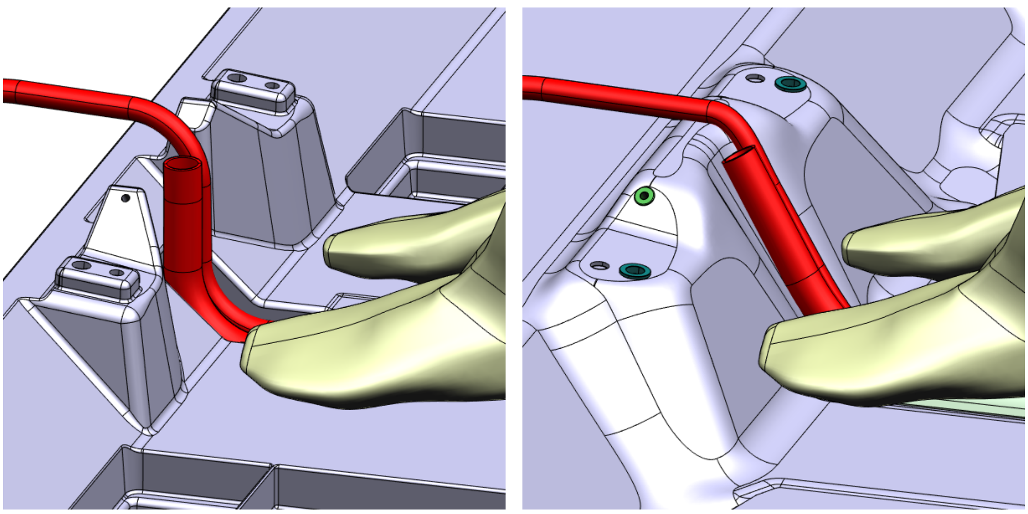


Figure 4.24: Image showing the coolant pipe in red. On the left, the pipe from the HPDC concept is shown, and on the right, the one from the HFQ concept is shown.

The coolant pipes are not at risk of being stepped on in this position, the concern is that the passengers toes might reach the coolant pipes, and therefore the vertical part of the coolant pipes might need a cover plate. The necessity for this cover plate is somewhat unclear, and it may be sufficient to cover the coolant lines with the footgarage's floor carpet.

The geometrical category also contains one desire. This desire states that the coolant pipe's route should remain the same in the HFQ concept as in the HPDC concept. While the same route has been taken in the HFQ concept, one modification to the pipe's fitting has been made. Due to the fact that the center tower forces the vertical part of the coolant pipes further back, the pipe fitting located in this area has been adjusted to accommodate the new angle of the coolant pipe. In summary, this indicates that the hose bracket is no longer considered a carry-over part. The modifications to the front pipe fitting can bee seen in red in Figure 4.25 below.

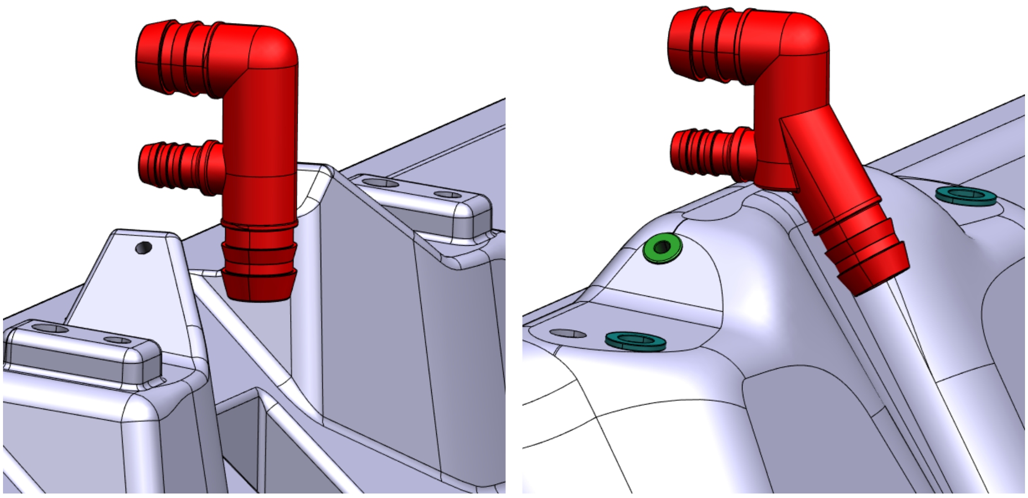


Figure 4.25: Image showing the front coolant pipe fittings in red. On the left, the pipe fitting from the HPDC concept is shown, and on the right, the one from the HFQ concept is shown.

4.3.1.3 User Needs requirement evaluation

The user needs category mostly consists of desires and one requirement which is fulfilled.

One of the desires is to keep the NVH levels to a minimum. According to the NVH experts at Volvo Cars, the main cause of NVH problems originating from the footgarage is static bending and static torsion of the battery. This means that a footgarage that reduces the overall bending and torsion of the battery also reduces the NVH of the car. For the bending analysis, the forces will be applied directly on the footgarage, while another vertical loads will be applied at the corners of one side of the battery tray to stimulate the torsion and displacement. After applying 3000N of force in both analysis, the torsional stiffness is 9,6% lower and the bending stiffness is 14,54% lower which means that the HFQ concept is less strong.

Another user need in the category pertains to the step length. As discussed previously in the report, the step distance of a BEV with a foot garage raises concern due to the substantial step created by the batteries' side beams. When measuring the step distance at the height of the concept's floor respectively, it amounts to 200.72mm for the HPDC concept and 229.33mm for the HFQ concept, indicating an increase of 28.61mm or 14.25% for the HFQ concept.

It's important to note that these measurements are not taken at the same Z coordinate (height), as the HFQ concept's floor surface is lowered. The draft angles in the HFQ concept cause the step distance to increase the lower you measure, see figure 4.26. Therefore, the step distance could be reduced by increasing the floor height, such as by using a thicker carpet. Another thing to note is that a large proportion of the increased step in distance also comes from the bending radii that the HFQ concept has, and these radii are not yet optimized. Hence, they could potentially be reduced, thereby reducing the step in distance as well.

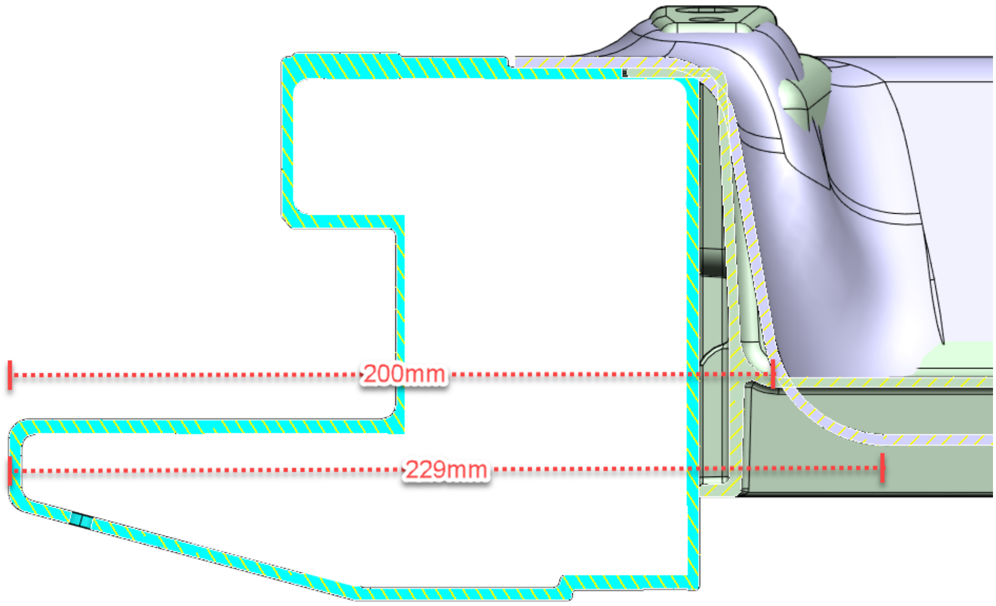


Figure 4.26: Image showing a cross-section of the HDPC (green) and HFQ (gray) concepts, visualizing the step distance from the side beam (turquoise) for both concepts. Note that the insides of the beam is hidden.

Another important aspect in the user needs category is the usable feet area. Measuring this can be tricky because the feet area and the floor surface of the foot garage are not the same. For example, the foot garage floor is not flat and requires carpets and covers to be added to form the usable feet area. To measure this, a flat, measurable surface with a boundary created from the foot garage walls was constructed in CAD for both concepts at the same height. This surface could then easily be measured and compared with the CAD tools. The measured feet area of the HPDC concept was 0.416m^2 and for the HFQ concept it was 0.36m^2, indicating a decrease of 13.46% for the HFQ concept.

Touching upon the previous point, the height of the feet area was lowered. The requirement specification stated that the feet area should remain the same. However, during discussions with the ergonomic experts, it was determined that the lowering of the floor would not matter and could easily be addressed by adjusting the carpet height. Because of this new insight, this desire was disregarded in the evaluation of the concepts.

4.3.1.4 Material requirement evaluation

The material chosen for the foot garage was selected in collaboration with Volvo Cars and ITL's material experts. Sheet alloy 6082 with a gauge of 2.7mm was chosen for the HFQ concept. This alloy meets all the requirements specified in the requirements specification, and aligns well with Volvo Cars recycling policies. Further explanation will be given in section 4.3.7.

4.3.1.5 Environmental requirement evaluation

Given that the largest contribution to carbon dioxide emissions arises from aluminium production, reducing emissions associated with that part entails minimizing the use of primary aluminium. This can be achieved in two ways: reducing the overall amount of aluminium used and by maximizing the utilization of recycled aluminium.

The combined weight of the HPDC foot garage and Y0 plate is 14.31kg. In contrast, the HFQ concept with its three cover plates weighs 6.32kg. In other words, the HFQ concept is approximately 7.99kg or 55.8% lighter than the HPDC concept, which aligns well with the requirements specified in this category.

It's worth noting that HFQ presents a significant opportunity to incorporate scrap metal into the alloy mix. Tests conducted by ITL indicate that the HFQ method is highly accommodating of this practice, with minimal discernible differences between parts made from recycled aluminium and those made from new aluminium. While implementing this approach on a large scale may not be feasible currently, it should be considered as a potential improvement for the future.

4.3.1.6 Feature requirement evaluation

The feature requirements are requirements on the footgarage that are related to specific features or functions that the footgarage have. For instance, it has to mount the seats with M10 bolts, the position of which cannot be changed because it is set by the seats department. Regarding these requirements all but one is satisified.

The requirement in question is: *"The part functions as a cell enclosure and must therefore be sealed."* In all the areas worked on, solutions have been implemented that, at least in theory, should fulfill this requirement. However, the project has a limited timeframe, and there was not enough time to address every area. Therefore, one question remains unanswered: the seat attachment guide holes. These are four holes, one for each seat attachment (see Figure 4.27), serving as guides for seat assembly. They position the seat attachment correctly before it is bolted down. The issue is that these holes do not have a bottom; in other words, they penetrate the battery enclosure. In the HPDC concept, these holes have a bottom, but due to the sheet metal design, this cannot be achieved in the same way. Due to time constraints, alternative solutions have not been explored.

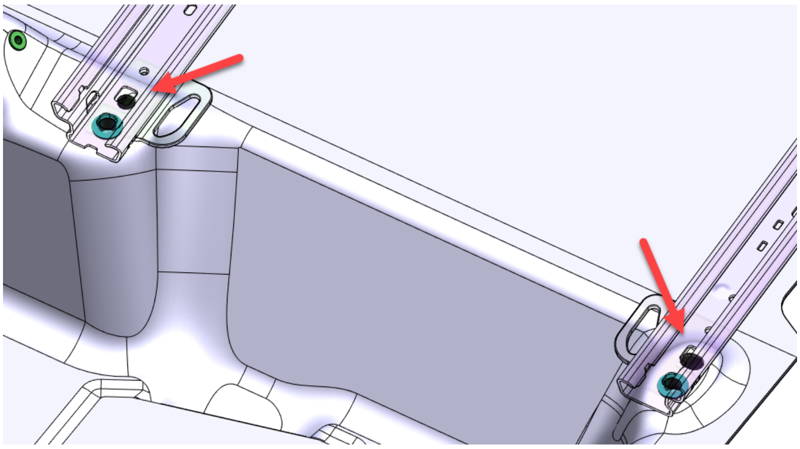


Figure 4.27: Image highlighting the guide holes in the HFQ footgarage located underneath the seat attachment rails (made transparent for visibility).

4.3.1.7 Functional performance summary

In order to more easily understand how the HFQ concept stands up to the HPDC concept regarding the functional performance, key points are summarized below in Table 4.4.

4.3.2 Sustainability

By comparing both the HPDC and HFQ concept in terms of CO_2 emissions, Volvo Car´s aspirations for the following years are that most of their vehicles should be manufactured with the lowest environmental impact, for instance, it is necessary to dig into both manufacturing processes and get a clear knowledge about the amount of pollution both processes produce per kilogram of aluminium manufactured. The amount of energy used per kilogram of aluminium in order to obtain a casted product is around 15 MJ [10] including the following sub-processes within the casting process:

The weight of the casted foot garage is 14,24 kg. If the energy used is in the overall casting process 15 MJ/kg according to [10] (see Figure 4.28, this can be calculated into 0,86 kg CO_2/kg, so the final amount of emissions per HPDC footgarage is 12,28

Point	HFQ	HPDC
Coolant lines	Possible kick protection required.	Safely routed
Step-in distance	229.33mm (14.35% longer than HPDC).	200.72mm
Usable feet area	0.36m^2 (13.46% less than HPDC).	0.416m^2
Aluminium alloy	25.42 (8.2% less than HPDC).	27.69kg
Recycling potential	High potential for scrap aluminium usage.	-
Sealing potential	IP67 rated. Seat alignment holes unknown.	IP67 rated
NVH/Strength	Static bending/torsion stiffness 14,54%/9,6% lower.	-

Table 4.4: Table summarizing the key points regarding the functional performance of the HFQ and HPDC conecpts.

Step	Considerations
Die	Comprehends the energy necessary for the design and manufacturing of the die used for the production of the casted part. Starts from taking a raw material and then shaped into the form for the final product, it is mostly divided into two dies that can go on top of the other or one in front of the other.
Metal	Refers to the amount of energy used for the scrap preparation or selection, use of raw metal or recycled material, and slag dross removal. Mostly focused in increasing the quality of material that will be used for the casting process.
Casting	The casting process consists of injecting the melted metal into the fixed chamber in order to get the final product or component.
Finishing	In this last stage of the manufacturing process is where some extra material is trimmed and separated from the final part so the extra material is taking again for reuse. It is also in this part of the process where extra polishing or removal of sharp edges are done.

Table 4.5: The different phases of a Life Cycle Assessment

kg CO_2. Based on results and findings from ITL´s experts gathered from a component produced and called Component A, with a mass of 17,9 kg. A total of 5 kg CO_2 where produced in the blanking, HFQ process, and cleaning and pre-treatment for the Component A, see Figure 4.29 for the complete breakdown. After applying simple math based on this, the amount of emissions for a 6,06 kg footgarage tub is 1,69 kg CO_2.

Both manufacturing processes have different sub-processes, and the amount of energy used is noticeably higher in the HPDC process. By simple comparison, the total of energy used in HFQ is 13,76% of the total energy used in the HPDC process. Seems promising for the company because the environmental impact is lower, able to use special material like recycled high strength alloys, with the possibility of blank optimisation, minimizing the use of primary aluminium and reducing the

	Die Prep	Metal Prep	Casting	Finishing	Total
Energy (MJ)	~0.5	3.0	3.2	1.2	7.9
Including loss (MJ)	1.5	-	9.7	3.7	14.9

Figure 4.28: Energy and emissions per one kilogram of cast final product.

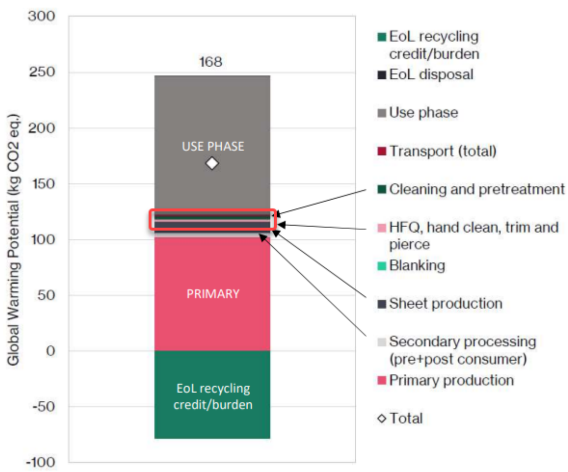


Figure 4.29: Cradle-to-grave analysis of the Component A. Notice that the small amount of emissions for the whole HFQ process is so little in comparison.

weight for the final product. After applying a comparison between both manufacturing techniques, HFQ seems the best option for Volvo Cars since it complies to the sustainability goals of the company.

4.3.3 Part Price

To conduct a part price comparison, data gathering from manufacturing, suppliers, procurement, design, etc., was necessary to gain price estimations of all parts comprising the two different concepts. To ensure a just comparison between the two manufacturing methods, all parts from both concepts were included in the price comparison. A detailed price breakdown can be seen in Tables 4.6 and 4.7 below.

Comparing the lists with the prices from the tables, it can be seen that the HFQ concept is 18.5% cheaper and 8.2% lighter compared to the HPDC concept. Keep in mind that the front and rear lids dilute these percentages, since they are both heavy and expensive parts that are very similar in price and weight for the two concepts.

4.3.4 Investment Cost

Since this process is new and if it is implemented in the company, a deep research about the investment was done estimating the prices for the necessary equipment. During the development process different process are involved in the HFQ process like, pressing, blanking, and heating but also extrusion, welding, and gluing. After

Component	Quantity	Price	Weight
Sheet Metal Tub	1	xx,xx€	6,06
Frontal Lid	1	xx,xx€	8,95
Rear Lid	1	xx,xx€	4,21
Front Crossmember Beam	1	x,xx€	3,37
Rear Crossmember Beam	1	x,xx€	2,58
Y0 Plate	1	x,xx€	0,07
Left Cover Plate	1	x,xx€	0,10
Right Cover Plate	1	x,xx€	0,10
High Strength Hexsert M10 Riveted	4	x,xx€	-
Total	-	xxx,xx€	25,42

Table 4.6: Prices of the parts that form the HFQ concept.

Component	Quantity	Price	Weight
Casted footgarage	1	xxx,xx€	14,24
Frontal Lid	1	xx,xx€	9,05
Rear Lid	1	xx,xx€	4,34
Y0 Plate	1	x,xx€	0,08
Screw M5x16x16,75	6	x,xx€	-
Total	-	xxx,xx€	27,69

Table 4.7: Prices of the parts that form the HPDC concept.

talking to different experts, Tables 4.8, 4.9, 4.10, 4.11 shows the amount for each process within HFQ.

Tooling	Price
Blanking die	xx xxx€
HFQ Form die	xxx xxx€
1st trim and pierce die	xxx xxx€
2nd trim and pierce die	xxx xxx€
Inspection fixture	xx xxx€
Robot	xxx xxx€
Ovens	xx xxx€
Total	xxx xxx€

Table 4.8: Prices for the tooling that comprehends the HFQ process. Information provided by Impression technologies.

Tooling	Price
Frontal crossmember beam	xx xxx€
Rear crossmember beam	xx xxx€
Total	xx xxx€

Table 4.9: Prices for the tooling for the extruded crossmember beams.

Tooling	Price
Friction stir welding	xxx xxx€
Arc Welding	xxx xxx€
Total	xxx xxx€

Table 4.10: Prices for the welding equipment.

Tooling	Price
Robot	xxx xxx€
Disperse gun	xx xxx€
Total	xxx xxx€

Table 4.11: Prices for the adhesives equipment.

Compiling the information shown on the tables, the total amount for Volvo Cars to invest, if the company decides to proceed with implementing this technology in the factory, will be a total of x xxx xxx EUR. Regarding the HPDC tooling, after talking with the design expert in charge of this part, according to his source, he mentioned that the total amount for the HPDC tooling will be x xxx xxx EUR. By simple comparison between both manufacturing techniques, the HFQ process is 38% cheaper in comparison to the HPDC.

4.3.5 Manufacturing Process Impacts

In evaluating the impact of manufacturing processes, particularly in the context of HFQ technology, the aim of this section is to assess each process within HFQ and make a fair comparison between both manufacturing techniques and propose possible improvements if necessary.

Constrains and Limitations of HFQ

When designing in HFQ there are some limitations or constrains that it must be necessary to be aware of before moving forward with the use of this technology. Most of the parts designed for HFQ are limited by several factors like material, size, shape, use, among others. For example, if the capacity of the oven just allows a

Processes within HFQ
Blanking of the alloy sheets.
Heating the material until SHT temperature.
Pressing and quenching.
Cleaning.
Ageing.

Table 4.12: Functional requirements of the crossmembers.

small quantity of blanks the process could take longer, another example is if the final product will be use for structural purposes or not which may affect the heating temperature and heating time and a proper design of the pressing dies. Another aspect to consider is the quenching during the pressing which is a process that must be controlled in order to avoid an undesirable microstructure in the final part, since the pressing cycle is too little, around 10 seconds. Lastly, not as crucial for the HFQ process but still part of it, the cleaning process limits the production too because it needs to remove every stain of oil and needs to be dry before going through the last step of the process which is the aging process.

Strategies for Increased Productivity
The changes that can be applied in every step of the HFQ process are numerous. For example, an additional step that could be applied during the blanking it could be applied laser cutting for trimming the most of the extra material. The limiting factor for throughput in the HFQ process is the oven. To increase production speed in a high-industrial setting, it is preferable to use a minimum of two ovens due to the slow heating process.

Another proposal for increasing the productivity is the handling process. For a basic HFQ process, a good option for handling the heated sheets is to use one robot arm between the oven and the pressing dies. Figure 4.30 shows a possible layout where the robot arm is located in the middle, the pressing dies and two ovens are located around the robot arm where it could be easy to move between ovens and place the material into the pressing dies. This example is just a proposal for increasing the productivity of the overall process. Another proposal for increasing the productivity is to have a continuous heater where the blanks are located in a moving band but the disadvantage is that a continuous heater needs a bigger area for it to be located.

Comparison HFQ vs HPDC
The HFQ process involves heating aluminum sheets to a high temperature, then rapidly forming and quenching them in a single operation. One of the limitations of HFQ is the size constraint and large parts are challenging to produce which restricts scalability. Additionally, the heating process is relatively slow, necessitating multiple ovens to enhance throughput in high-volume production environments, among other limitations.

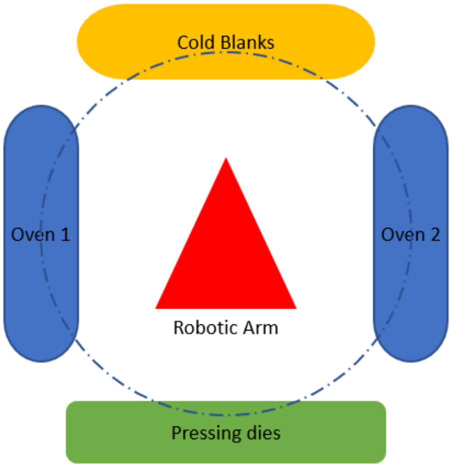


Figure 4.30: Simple proposal for placing a robotic arm in between several ovens.

HPDC involves injecting molten metal into a mold under high pressure, allowing for rapid production of complex and precise shapes. The high pressures involved can also lead to porosity and incomplete filling of the mold and the dies are subject to thermal fatigue and wear, which lead to frequent maintenance or replacement, increasing operational costs. Another challenge is the initial setup cost, as creating the precision molds is expensive and time-consuming, making HPDC less suitable for low-volume production. This comparison states that a final product obtained by HFQ can be less complex in terms of manufacturing and provides a better handling for the tooling or pressing dies.

Impacts in Volvo Cars´ factory
If Volvo Cars decides to use this technology inside the factory, it would be necessary to install new equipment and modify existing production lines. Since this process requires heating the material then the installation of two ovens should be the most reasonable first action, followed by installing new presses or modifying existing ones by installing cooling channels for the quenching of the material. For the cleaning process, it needs to provide a deep cleaning for removing the oil and at the same time needs to process the residual liquid for sustainability purposes. Installing all of these equipment will imply in doing some configuration to the factory layout at first minimizing development issues while developing new HFQ parts.

4.3.6 Time to Market

The time to market can vary depending on how Volvo Cars would like to proceed with the use of this technology. According to ITL´s partnership with different companies around the world, there are several producers within Europe and China that possess the use of the technology in-house and could provide help if there is the need for a new development of a component. By contacting these partners, they could provide support for concept development, manufacturing simulations, design optimization, factory simulation, and other services that could benefit the overall process.

The time to market, if considering a supplier, it could only refer to the concept development for a new part until confirming its formability at a 100% with a proper material selection and optimization. Once the part is developed, the supplier could proceed with the development of the pressing dies and start with the HFQ manufacturing process.

The time to market, if considering the possibility of in-house manufacturing, this involves the implementation of the HFQ technology in Volvo Cars. This technology transfer, according to ITL´s experts, could take around 2 years and during that time the supplier can provide lessons to Volvo Cars employees about how to develop in HFQ considering aspects like formability, material, pressing dies development, and aspects regarding the whole process.

4.3.7 Material Base

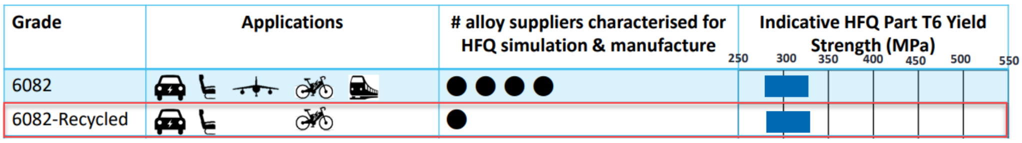
Hot Form Quenching is a versatile manufacturing process able to process different types of alloys and in order to be used, it must go through a HFQ accreditation process. For a proper evaluation of a particular material, according to ITL, the material must be studied and taken through an accreditation process to secure a proper manufacturing and application that could vary depending on the type of industry the final part is related to, like automotive, aviation, transport, minor vehicles, technology, etc. The accreditation process are outline in Table 4.13 below.

HFQ Accreditation process
Selection/Reception of the material.
Chemical composition analysis.
Solution heat treatment and ageing assessment.
Material card creation.
Simulations.
Results validation.
Press simulations.
Ageing process.
Final results and HFQ accreditation.

Table 4.13: The different phases of a Life Cycle Assessment

As the owner of the technology, ITL managed to create several material cards accrediting a list of materials ready for the application of HFQ with recycled versions of specific materials. Figure 4.31 shows the material applied for this thesis and a recycled version of it showing that there are no differences in the mechanical properties.

One important disadvantage of this recyclable material is that it is not produced by a large amount of suppliers. Several suppliers were accredited by ITL for the



Grade	Applications	# alloy suppliers characterised for HFQ simulation & manufacture	Indicative HFQ Part T6 Yield Strength (MPa) 250 300 350 400 450 500 550
6082		● ● ● ●	
6082-Recycled		●	

Figure 4.31: List of materials accredited for HFQ according to ITL.

use of different types of alloys for different applications but only one offers 100% recyclable 6082 alloy, this company is called Gränges and it seems the only company that produces AA6082-R 2.5mm coil in the conventional way. However, there is no confirmation about this since Gränges just supplied recycled aluminum for research purposes to ITL.

According to ITL´s experts, the best material for this project is AA6082 due to its wide range of applications within the automotive industry and due to previous experiences from parts produced for different ITL´s automotive customers. This alloy is the most informed and accredited alloy for HFQ with production data since 2016 and providing a good balance of strength and ductility, with a low amount of copper which eases the formability during the pressing process. Since this analysis is considering a primary AA6082, it provides a very good foundation and choice criteria when moving forward with the use of the AA6082 recycled raising the sustainable applications for Volvo Cars.

Comparing both processes in terms of material base, according to the HFQ footgarage assessment criteria, results in the following statement: both processes can use primary and recycled material, since there is no difference in the mechanical properties which is the most important factor for material selection.

5
Conclusion

As stated, the aim of this study was to perform an A-to-B comparison between the two concepts. When examining this comparison, it is important to consider that the concepts are developed to varying extents. One obvious example is that the HFQ footgarage does not have an implemented solution for sealing the battery via the alignment holes. Another point to consider regarding these differences in the degree of development is that the level of optimization varies. For example, no optimization has been done on the HFQ footgarage. This means that when a function was considered functional, development ceased, and the focus shifted to the next function. Consequently, no major effort was put into reducing weight or increasing strength in the HFQ footgarage.

Overall, the HFQ method seems promising. During the short development time available, the HFQ concept appeared to be very competitive with the HPDC concept in the A-to-B comparison. The main drawbacks of the HFQ concept compared to the HPDC concept in terms of performance were a longer step-in distance, a smaller foot area, and worse NVH performance. Some small optimizations of the HFQ concept are possible regarding the step-in distance and foot area. This could be done by adjusting the draft angles and radii around the footgarage walls. Regarding NVH performance, many potential optimizations could be made. For instance, ribs could be incorporated at strategic locations around the large flat surfaces of the footgarage. These ribs would reduce the static bending and static torsion of the HFQ concept, the main contributors to NVH. Another way of optimizing is through the crossmembers, which were only simulated to withstand swelling forces and have not been evaluated from an NVH perspective.

The HFQ concept's main advantages are also clear. The overall concept is both lighter and cheaper, two of the most valuable criteria for a battery electric vehicle customer. The price of the concept could also be improved. Since the HFQ method creates its own temper on the parts, it is not necessary to buy sheet metal that is already tempered. An already tempered sheet metal is both more expensive and completely unnecessary when using the HFQ method. However, since the price of untempered sheet metal is unknown to Volvo Cars, this was not included in the calculations. To achieve this price optimization, a custom deal with the aluminum suppliers has to be made. Another major advantage is the potential for sustainability. As proven by ITL, large amounts of scrap metal could be mixed into the aluminum alloy without any performance loss in the sheet metal. Additionally, using strong aluminum often requires less material, resulting in a smaller carbon footprint for the part. These two points combined present a significant advantage in the sustainability of the HFQ process compared to the HPDC process.

Digging more on the sustainability aspect, The amount of CO_2 emissions per part produced is too low and there is a high possibility that could be applied in different pars of many different car models. By doing this, the environmental impact could be reduced per car model and since this is connected to the amount of material used, this could approach the company more towards the sustainability goals and at the same time increasing the performance and range of the vehicle or even better: use fully recycled parts in the future.

In case the company decided to develop HFQ components with the help from a supplier, could reduce the time-to-market development and focus entirely in developing and optimizing for a better performance in the vehicle. If necessary, Volvo Cars could use different types of high strength alloys apart from AA6082 by following the accreditation process established by ITL and select a specific type of alloy for a specific part located in a specific place within the vehicle.

Overall, the HFQ method has made a good impression. It has great potential in contexts like the footgarage and similar applications. With sufficient development efforts, it is believed that the HFQ concept could contribute to increased performance of the electric car.

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A
Appendix 1

Master Thesis Timetable

Activity	January					February				March				April				May				
	1W	2W	3W	4W	5W	6W	7W	8W	9W	10W	11W	12W	13W	14W	15W	16W	17W	18W	19W	20W	21W	22W
Concept definition																						
Concept refinement																						
Project dokumentation																						
Project start																						
Prestudy																						
Problem Definition																						
Requirement listing																						
Concept modeling																						
Model refinement																						
Model simulations																						
Planning report writing																						
Planning report handin																						
Half time demo presentation																						
Final report writing																						
Final presentaion preparation																						
Final presentation																						
ITL Introduction																						
ITL Study visit																						
First concept model done																						
ITL Weekly Design meeting																						
TCvis Crashcourse																						
FSW Course																						
Catia course																						
Cad standards course																						

B
Appendix 2

CHALMERS UNIVERSITY OF TECHNOLOGY

PLANNING REPORT

IMSX30

Design a high-voltage Battery Enclosure system using a new manufacturing method

Authors
Charlie NILSSON, Daniel OSORIO

January 22, 2024

CHALMERS
UNIVERSITY OF TECHNOLOGY

Contents

1 Introduction

This report serves as a crucial tool for aligning our objectives, methodologies, and expected outcomes. Our aim is to provide a clear and structured approach to the project, ensuring that every stage is meticulously planned and executed.

The core of the report focuses on the proposed strategies and methodologies. Here, we explain our chosen approach, the rationale behind it, and how it aligns with our overall goals.

A critical aspect of our report is the timeline, which provides a detailed schedule of activities and milestones. This timeline is designed to keep the project on track and ensure timely delivery of results.

2 Background

The primary challenge with high-strength aluminum alloys used in structural parts is that they're not easy to shape and tend to spring-back when formed at room temperature. This makes it difficult to create complex shapes using traditional cold forming methods.

However, if we attempt to shape them at higher temperatures, it solves the shaping problem but can cause the alloy to age prematurely. This early aging may lead to unexpected changes in the alloy's mechanical properties. To counteract this, we need to apply a controlled aging treatment separately after forming. So, we address one problem, but in doing so, we introduce another: the controlled aging process can cause the formed part to warp.

This is where Hot Formed Quenching (HFQ) comes in. HFQ combines hot forming and quenching within the press itself. This solves the remaining issue of warping in hot forming aluminum. So, HFQ offers a combined solution to the problems that arise when working with high strength aluminum alloys. It shapes the aluminum at elevated temperatures to reduce spring-back and controls the aging process without causing warping by quenching the part while it remains in the press.

HFQ is a relatively new manufacturing method that promises increased design freedom, reduced spring back, greater lightweighting, and lower investment costs. As Volvo Cars transitions towards a fully electric era, these advantages become crucial. Lighter vehicles and lower costs directly impact what customers value most when buying an electric car: mileage and price.

3 Task

Our job is to explore how HFQ can be used in the large battery components of upcoming Volvo Cars. Specifically, we're focusing on a part called the "foot garage." This is a tub-like structure placed in the middle of the battery in certain car models. In these car models the battery enclosure architecture includes the foot garage to enable better comfort for the rear seat passengers. To do so there's a need for a cutout in the large electric vehicle battery that runs along the car's underside. Instead of shortening the battery, it is split into two parts, with the foot garage sitting between the battery compartments. This concept allows for both passenger comfort and efficient use of battery space.

There is currently a concept model of the foot garage designed for casting. Our task is to create a new version of the foot garage that can be manufactured using HFQ. This challenge requires redesigning the foot garage from scratch. It must meet certain unchangeable requirements, and ideally, we should keep some existing features. The current design includes shapes that can't be achieved with sheet metal stamping, so we need new solutions for these parts of the foot garage. Additionally, the foot garage serves as a seal for the battery cell compartments, which means it must have a geometry that can be properly sealed with the rest of the battery hardware. These are just a few of the things that need to be considered.

The first stage of this project is to create a concept definition. This involves researching and learning about the HFQ method and its design limitations, identifying and documenting related requirements, creating an idea of the part in questions and its surrounding parts in the concept car. After that is done an initial concept model can be designed in CAD.

The second stage of the project is concept refinement. In this phase, we will simulate and iterate over the model to refine it according to the requirements defined in the first stage. Throughout this process, we will work closely with Impression Technology (ITL), the British company behind the manufacturing process, to ensure the part's feasibility. Weekly design meetings will be held to discuss the model, and the model will also be sent to ITL for simulation in their software.

The third and final stage is to evaluate and document the project. The final model will be evaluated based on the requirements of the foot garage, and an assessment of HFQ's potential to be used in a replacement of the foot garage will be made. During this stage, the project report will be finalized. Additionally, a final presentation detailing the project's progress and its results will be conducted.

4 Aim and Objective

The specific objective of the project is to redesign a high-voltage enclosure part to be manufactured using HFQ technology. The aim is to perform a comparison between this part manufactured by HFQ and the same part produced through casting and cold forming, to assess the potential benefits of HFQ.

If we are successful in creating a version of the high-voltage enclosure part using HFQ, this could lead to numerous improvements of the part. The HFQ technique is known for its many potential benefits, all of which are attractive to Volvo Cars and are therefore targeted goals in the design process. However, it's important to note that these benefits are aims rather than strict requirements. They will be considered as key assessment points at the end of the study.

In Table 1 is a list of assessment points that the project aims to improve upon, highlighting the potential benefits that HFQ offers.

Assessment Point	**Description**
Sustainability	HFQ technology may use less pure aluminum, incorporating a higher concentration of recycled aluminum. This could lead to up to a 95% reduction in emissions. The exact amount of recycled material usable needs further investigation.
Cost Reduction	The HFQ method reduces costs primarily through less material usage for complex structural parts and fewer parts needed due to its ability to form intricate geometries from high-strength aluminum.
Manufacturing Process	The new hot forming process differs from traditional die casting. Differences in investment cost, throughput, production costs, etc., need investigation.
Mass Reduction	HFQ could lead to a 20%-50% weight reduction in parts, crucial for electric vehicles as it enhances performance and extends driving range.
Attributes & Functions	Switching to HFQ will affect the performance of parts. Assessing changes in function and related parts is essential to understand the method's value.
Supply Base for Materials	With HFQ's capability to use more recycled aluminum, sourcing this material responsibly is vital, aligning with Volvo Cars commitment to environmental friendliness.
Time to Market	As HFQ is new to Volvo Cars, assessing the method's applicability and determining its utilization timeline is critical for project planning.

Table 1: Assessment Points and Potential Benefits of HFQ

In addition to these aims/assessment points, this project also aims to establish a valuable partnership with a new supplier and expand the knowledge of the R&D department. This could be beneficial for future development projects.

5 Demarcations

The project operates within certain constraints and limitations. Understanding these boundaries is essential for setting realistic expectations and focusing our efforts on achievable goals. In Table 2 below, we provide a detailed list of the most profound limitations that will shape the course of this project.

Limitation	**Description**
Time	The study is limited to a timeframe of 5 months, which might impact the depth of research and limit the exploration of various potential design variations. This timeframe may also constrain the expansion of HFQ's application to other parts.
Budget	There is no dedicated budget, but resources are available from Volvo Cars on an as-needed basis. If we require resources, we can request them and they will be granted on a case-by-case basis.
Resources	The master thesis students leading the project, the experts from Volvo Cars, and the supplier ITL.
Technology Constraints	The study will primarily use software like CATIA V5 and TeamCenter, alongside a new simulation tool developed by ITL.
Project Focus	The research focuses on the design of the "foot garage" battery enclosure part, and does not extend to other related parts. However, efficient time management may allow for the extension of the analysis to adjacent parts.
Industry Standards	The project will adhere to various industrial standards related to car battery manufacturing, including Volvo Cars and ITL design guidelines, as well as other international standards that may be relevant.
Industry Application	The research will concentrate solely on applications within the automotive industry context.

Table 2: Project Limitations

6 Methodology

The methodology employed for the realization of this project is structured in revising scientific literature, CAD modeling, consultation with experts, and simulations.

The research methodology contains a thorough review of numerous scientific papers and studies related to HFQ. This involves an examination of how the process is executed, production criteria, and other relevant aspects. A portion of the literature encompasses publicly available information released by companies that have previously experimented with this process.

The primary focus of the projects second phase involves creating virtual models for subsequent simulations aimed at deriving an optimal concept that aligns with various design and manufacturing criteria. The majority of this modeling process will be conducted utilizing Volvo Cars facilities, with ongoing communication with external suppliers to receive feedback for continuous improvement.

External experts play a crucial role in executing proper simulations for the HFQ process and analyzing the proposed concepts behavior. Internal experts contribute valuable insights into manufacturing process costs, material considerations, design modeling, and more. By combining various production aspects, significant feedback is generated, influencing the entire supply chain production. This collaborative approach ensures a comprehensive understanding of the project's intricacies and facilitates informed decision-making throughout its execution.

7 Timetable for Thesis Production

In Figure 1 below you can see a preliminary timeline for the project. This is an estimate of the tasks that need to be completed and how long they are expected to take. This timeline will be modified and updated as the project progresses, serving as a guide to help us stay on track.

8 Societal, ethical and ecological aspects

According to internal standards and regulations, Volvo Cars places a significant emphasis on understanding the ecological impact of its products today. One notable action taken in this regard is the requirement that all materials used in car manufacturing must adhere to a certain level of recyclability, approximately 35%, as indicated by internal experts. It is essential, however, that this commitment to recyclability does not compromise the mechanical

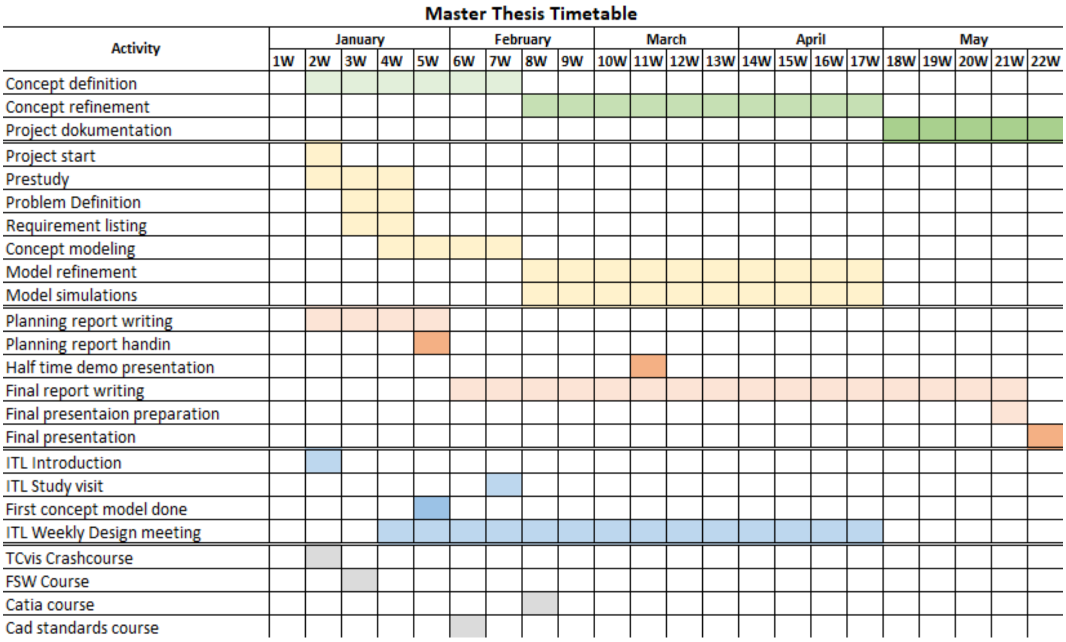

Figure 1: Timetable showing the planned thesis project

properties of the materials, particularly in terms of safety, for instance, this aspect will be closely analyzed in this project.

Volvo Cars is currently on an ongoing journey towards achieving circularity by the year 2040. The shift towards a more circular approach is driven by the understanding that it is not only beneficial for the planet but also aligns with Volvo Cars business model. The aim is to generate more circular revenue while minimizing revenue obtained through the use of primary resources. In this context, the project is firmly aligned with the circular way of thinking and is integral to Volvo Cars broader circularity goals.

Finally, in accordance with internal ethical regulations, any prospective association between Volvo Cars and the external supplier, responsible for assisting with the HFQ simulation, is contingent solely on the technical expertise that the supplier can offer to Volvo Cars for future applications. In this context, the business-to-business (B2B) relationship aligns seamlessly with Volvo Cars ethical standards.

9 Conclusion

The exploration of Hot Form Quench (HFQ) technology as an alternative manufacturing method and its potential might be a very promising solution for Volvo Cars and the challenge of this project is to prove it. Otherwise, it will be stated the reasons why it should not be implemented.

The project's focus on redesigning the "foot garage" component using HFQ technology might enhance Volvo Cars transition towards electric vehicles. The potential benefits, such as reduced weight and lower costs hold significance in increasing electric vehicle performance and competitiveness in the market.

The project establishes a robust set of assessment points, ranging from sustainability and cost reduction to manufacturing process changes and mass reduction providing a comprehensive framework when evaluating the effectiveness of HFQ technology in comparison to traditional manufacturing methods used nowadays in the factory.

The limitations described, including time constraints, budget considerations, and technology constraints, highlight the challenges inherent in the project. Addressing these challenges presents opportunities for Volvo Cars to develop a valuable partnership with suppliers and expand the knowledge base of the Research and Development (R&D) department for future projects.

C
Appendix 3

HFQ Footgarage Requirement Specification

Project Goals

The objective of this project is to develop a conceptual alternative to the existing "footgarage". This new concept is expected to fulfill the same functional criteria as its predecessor. The distinguishing factor between the two concepts will be the method of manufacturing. Specifically, the novel concept will be produced utilizing the new manufacturing process called Hot Form Quenching.

Stakeholders

In the development project, there are three principal stakeholders: the customers, Volvo Cars, and Impression Technologies. Each stakeholder possesses unique interests concerning the project's outcome. A successful outcome of the project has the potential to influence the vehicle's price and performance, directly impacting both the customer and Volvo Cars. For Impression Technologies, this could result in the establishment of a valuable customer relationship.

Functional Requirements

Describes what the part should do, such as specific functionalities and behaviors of the end product.

No.	Description
1	The footgarage serve as a structural element within the battery tray assembly.
2	The footgarage provides a floor surface for the rear passengers feet.
3	The footgarage act as an enclosure for battery cells.
4	The footgarage provides mounting points for the front seat.
5	The footgarage includes mounting points for attaching the center console.
6	The footgarage incorporate cooling pipes for the battery's rear portion.

Technical Requirements

Defines the technical requirements and frameworks that the project must adhere to.

No.	Description	Justification	Value	Unit	Class
		Dimensional			
1	Tub width	Needs to fit between the side beams of the battery.	+621	mm y	Req.
2	Tub height	Needs to be contained within the top and bottom batteryplanes.	111	mm z	Req.
3	Tub front/rear wall position	Has to support the battery cells at specified planes.	+3163/+3677	mm x	Req.
		Geometrical			
4	Seat attachment position	The front seat attachment points must be fixed in position.	-		Req.
5	Seat attachment geometry	The seat attachment geometry should not interfere with FSW.	-		Req.
6	Cooling pipes protection	The cooling pipes must be protected from the rear passengers feet.	-		Req.
7	Cooling pipes position	Should remain unchanged to avoid interference with other parts.	-		Desire
8	Cooling pipes mounting	Cooling pipes must be safely routed through the design of the part.	-		Req.
9	Minimum male radi	Minimum male bend radius that HFQ can accommodate.	2t	mm	Req.
10	Minimum female radi	Minimum female bend radius that HFQ can accommodate.	t	mm	Req.
		User Needs			
11	NVH levels	Low levels of NVH increase passenger comfort.	Low		Desire
12	Step lenght	A short step length will improve the ergonomics of entering the vehicle.	Short		Desire
13	Thermal protection	The footgarage must be thermally safe in the event of a battery fire.	-		Req.
14	Foot area	Maximizing the foot area for passengers will enhance comfort.	≥0.398	m2	Desire
15	Foot position in Z	The height of the foot position is a determinant of comfort.	+329	mm z	Desire
		Material			
16	Sheet metal thickness	Sheet metal thickness compatible with HFQ capabilities.	>3.8	mm	Req.
17	Alloy type	The 6xxx and 7xxx series are suitable material options for HFQ processes.	-		Req.
18	Source	The material source must adhere to Volvo Cars standards.	-		Req.
19	Ideal alloy type	The 6xxx series complies with Volvo Cars recycling policies.	6xxx		Desire
		Environmental			
20	Eco friendly design	By reducing the amount of sheet metal waste, CO2 emissions are minimized.	10	%	Desire
21	Recycled material	Less raw aluminum results in lower CO2 emissions.	80	%	Desire
		Features			
22	Environmentaly sealing	The part functions as a cell enclosure and must therefore be sealed.	-		Req.
23	Structural element	It good id it provides structural support to the battery tray.	-		Desire
24	Number of parts	It reduces manufacturing costs.	>3	parts	Desire
25	Seat attachment force	The attachments must withstand a specified force for safety.	4/7; 18/14	kN	Req.
26	Seat mount	The seat mounts with M10 bolts.	M10		Req.
27	Cells sweling forces	Must withstand front and rear cell sweling forces.	200	kN	Req.

Regulatory Requirements

Includes any legal or compliance standards relevant to the project.

No.	Description
1	VCS 5027,1 Product Computer-Aided Design Standard CATIA V5
2	VCS 5080,3 Cut corners, radii and cut-outs

D

Appendix 4

HFQ Footgarage Assesment Criteria

Project goals

The objective of this project is to develop a conceptual alternative to the existing "footgarage". This new concept is expected to fulfill the same functional criteria as its predecessor. The distinguishing factor between the two concepts will be the method of manufacturing. Specifically, the novel concept will be produced utilizing the new manufacturing process called Hot Form Quenching while the old concept are designed to be manufactured using High Preasure Die Casting.

Purpose

To objectively compare Hot Form Quenching with High Pressure Die Casting, a thorough evaluation of both methods is required. The comparison should be based on criteria that are relevant to Volvo Cars. This document aims to clearly define the assessment points listed in the projects definition, and will act as a guide during the evaluation phase of the project, where the two concepts are to be compared.

Assesment criteria

The following definitions specify the boundaries of what each criterion will assess and describe the methodologies by which these assessments will be conducted.

Function Performance

The function performance is evaluated by assessing how well the functional requirements are met. The evaluation will consider the necessary steps taken to fulfill the functional requirements in both concepts. It will also compare the degree to which the desires in the requirement list are fulfilled, which will act as an objective value of performance.

Sustainability

To assess the sustainability of the two concepts, a Life Cycle Assessment (LCA) will be conducted. This will generate measurable metrics related to the emissions produced by the part over its lifetime, allowing for direct comparison between them. For instance CO_2 emissions per kilogram of aluminium used.

Part Price

The part price will be assessed by deriving a price per individual part. To estimate this value, the material cost, the manufacturing cost, and the human labor will be estimated. This also includes long-term costs spread out over a period, such as machine maintenance.

Investment cost

The investment cost will be established by investigating and combining the major investments necessary to initiate the production of the concepts. It will include tool pricing, machine acquisition, installation costs, staff training, safety inspections, etc. These approximations can then be directly compared to each other.

Manufacturing process impacts

The impact of manufacturing processes will be measured by listing the processes related to HFQ and comparing which processes are necessary to be installed, added, or removed in the manufacturing line. Following the assembly of the footgarage concepts, the production line will be measured in terms of cost, throughput, time, downtime, among other factors.

Time to Market

The time to market will be quantified by calculating the duration required to introduce both concepts to the market, taking into consideration factors such as tool manufacturing, machine acquisition, and production implementation.

Material Base

The material base will be evaluated by comparing the materials that can/will be used in the two concepts. They will also be compared in terms of the original sources of the raw materials by applying traceability to the suppliers and assessing their flexibility in delivering materials to various destinations, analyzing delivery flexibility.

<u>Possible extra criteria:</u> Risk Assement, Flexibility, Quality Control, Energy Efficiency, Material Usage.

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