# Development of Foot Design for Gasketed Plate Heat Exchangers

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MASTER THESIS

# Development of Foot Design for Gasketed Plate Heat Exchangers

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# Abstract

In the process of making the industry more energy efficient, the gasketed plate heat exchanger has an important role as it effectively transfers heat between fluids. This master thesis aims to investigate and develop a new supportive foot for Alfa Laval's gasketed plate heat exchangers. The goal was to present a design that can sustain severe external loads induced by for example the connecting piping system or earthquakes. Beyond sustaining the severe loads, the foot was also required to maintain a high serviceability and a low cost. The project covered in this report follows a development process where eleven different concepts were generated and scored. The most important factors in the developed concepts were cost, manufacturing, and serviceability. Two concepts emerged from the scoring and was further developed to test their feasibility. From the in-depth development one concept remained and was considered the best design. The design was then modelled in a FEM program together with an existing design to verify the stresses in the used bolts in the foot. In the verification of the design, it was concluded that the new design reduced the usage in the attached bolts in the foot by up to 67%, compared to existing designs. It was also found that preloading the bolts made the model less tolerant to the severe loads. Furthermore, adding a higher frictional coefficient to the model decreased the usage in the studied bolts.

**Keywords:** Heat exchanger, bolted joints, product development, FEM.

# Sammanfattning

I arbetet med att göra industrin mer energieffektiv har packningsförsedda värmeväxlare en betydande roll då den effektivt överför värme mellan fluider. Detta exjobb ämnar at utreda och utveckla en ny stöttande fot till Alfa Lavals packningsförsedda värmeväxlare. Målet var att ta fram en design som kan klara av allvarliga externa laster genererade av till exempel ett anslutande rörsystem eller jordbävningar. Utöver att klara de alvarliga lasterna, skulle foten också bibehålla en hög servicebarhet och en låg kostnad. Projektet beskrivet i denna rapport följer en utvecklingsprocess som skapade och bedömde elva olika koncept. De viktigaste faktorerna i bedömningen var kostnad, tillverkning och servicebarhet. Två koncept togs vidare från bedömningen för vidare utveckling och test av dess genomförbarhet. Från den fördjupande utvecklingen kvarstod sedan ett koncept som blev ansett den bästa designen. Designen modellerades sedan i ett FEM-program tillsammans med en redan existerande design för att verifiera spänningarna i bultarna i foten. I verifieringen fastslogs det att den nya designen reducerade användandet av bultarna med upp till 67% i jämförelse med den redan existerande designen. Det sågs också att förspänning av bultarna gjorde modellen mindre tålig mot de svåra lasterna. Vidare fastslogs det att ett högre friktionstal i modellen minskar spänningarna i de studerade bultarna.

**Nyckelord:** Värmeväxlare, skruvförband, produktutveckling, FEM.

# Acknowledgments

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Lund, May 2022

Daniel Rundström

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# List of acronyms and abbreviations

| | |
|---|---|
| **AB** | anchor bolt |
| **API** | American petroleum institute |
| **ASME** | American society of mechanical engineers |
| **B2B** | business-to-business |
| **B2C** | business-to-consumer |
| **CB** | carrying bar |
| **EPD** | existing product development |
| **FP** | frame plate |
| **GPHE** | gasketed plate heat exchanger |
| **HVAC** | heating, ventilation, and air conditioning |
| **ISO** | International organisation for standardization |
| **NPD** | new product development |
| **NPS** | nominal pipe size |
| **PB** | plate bolt |
| **PHE** | plate heat exchanger |
| **PP** | pressure plate |
| **UA** | uppfinningsanmälan (eng: invention request) |
| **U&E** | Ullrich and Eppinger |

# 1 Introduction

## 1.1 Background

### 1.1.1 Alfa Laval

Alfa Laval is a global company with three key product areas: heat transfer, separation, and fluid handling. The company have sales in more than 100 countries and during the year 2021 order intake was above 45 000 million SEK. The head office is located in Lund, Sweden, where a major part of the research and development of plate heat exchangers (PHE) is done. This is where the master thesis will be carried out. Globally Alfa Laval employs about 17 000 people, about 2 400 in Sweden and just over 1 000 of them in Lund (Alfa Laval, 2021). Alfa Laval focuses on accelerating success for its customers, people, and the planet. They aim to be responsive to customer's needs and strive to go the extra mile to support them. Alfa Laval's products support industries to purify, refine and recycle material. With this, Alfa Laval's technologies aims to promote a responsible use of natural resources and the drive is to help reduce the environmental impact of most industrial processes through improved energy efficiency and heat recovery (Alfa Laval, 2022a)

### 1.1.2 Gasketed Plate Heat Exchanger

A major product within one of Alfa Laval's key technologies, heat transfer, is the gasketed plate heat exchanger (GPHE). A GPHE consists of a frame and several corrugated metal plates with gaskets in between, and one of Alfa Laval's GPHEs can be seen in Figure 1 below. The corrugated plates are called channel plates and are used to perform the heat transfer between, most commonly, two different fluids. The frame of a GPHE is the combined name of the components used to retain the pressure within the heat exchanger. Main components in the frame are the frame plate (FP), pressure plate (PP), carrying bar (CB) and the feet. FP and PP are thick solid metal plates that exist at the front and back of the GPHE, coloured blue in Figure 1. The FP is the plate in the front and the PP is the plate in the back. The CB is the beam in the top of the GPHE, attached to the FP, where all channel plates and the PP hang from. Feet are attached to the FP and PP to support the GPHE.

**Figure 1: Industrial gasketed plate heat exchanger from Alfa Laval (Alfa Laval, 2022b)**

The purpose of a heat exchanger is to efficiently increase or decrease the temperature of most commonly, a fluid. The process uses a hot and a cold fluid that is distributed on opposite sides of the corrugated plates inside the PHE. In Figure 2 a schematic of the process in a GPHE is seen. Inside the GPHE, heat is transferred from the hot fluid to the channel plate and then further on to the cold fluid. This ensures that no contact is made between the different fluids. Gaskets are used to keep the fluids in between the plates and guide the fluids through the GPHE (Alfa Laval, 2022b).

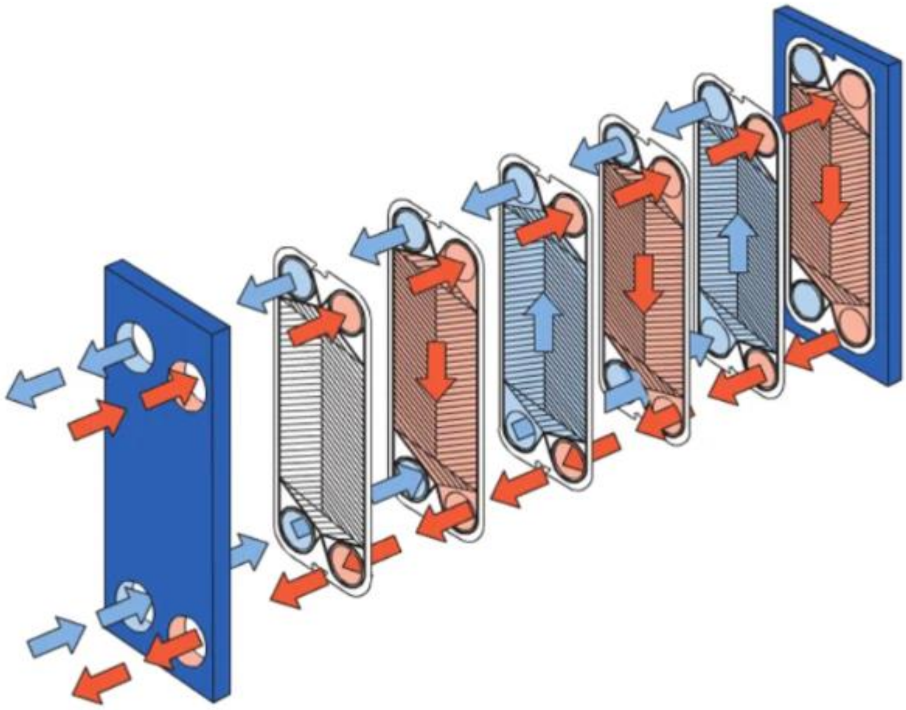

**Figure 2: Schematic image of the flow of hot and cold fluids in a GPHE, where red indicates a hot fluid while blue indicates a cold fluid (Alfa Laval, 2022b).**

## 1.2 Problem Description

When in operation a GPHE can be exposed to various external loads such as pressure and vibrations from the connecting piping system, wind loads or even the loads from an earthquake. In order for the GPHE to sustain these external loads it has to be well anchored to its foundation. Currently, anchoring of Alfa Laval GPHEs is done with the component named foot. Even though several sizes and designs of feet exist in Alfa Laval's product range, larger GPHEs have had issues with sustaining the most extreme external loads, using the current foot designs in the standard product range. The standardised reinforced foot has been too weak when validated through calculations and the serviceability is limited. This has led to orders with these requirements have to be prepared by a specialised department, something that requires extra time and resources.

## 1.3 Project Objective

The objective for this master thesis is to investigate current feet designs for GPHEs and develop a new design with good service functionality. The design has to sustain severe external loads and be applicable for the larger GPHEs. The aim is to support the most severe external loads included in the standard product scope. The work in the master thesis aims to further improve the already existing GPHEs with a foot design that improves serviceability and can be included in the standard product range. This would cut costs and reduce time during service.

## 1.4 Limitations

The project is limited to specific products and verification methods. Firstly, the project is limited to only large industrial GPHEs, which in practice means GPHEs with a port hole size of more than 350 mm, from Alfa Laval's industrial range. These products are the T35, T45 and T50.

Secondly, the project is limited to components verified in regard to the standards from the American Society of Mechanical Engineers (ASME). This includes pressure vessel and pipe connection standards. The calculations regarding external loads will be limited to standard API 662 Part 1/ISO 15547-1. These standards will be described later on.

Furthermore, the project will not have the possibility to conduct physical testing of concepts. All testing will be simulated in a virtual environment.

# 2 Theory

*Unless stated, information in this chapter is gathered from internal resources within Alfa Laval.*

## 2.1 Coordinate system

Throughout this project, directions for dimensions and loads are used with a base in a uniform coordinate system, visualised in Figure 3. The horizontal directions are the X- and Y-direction where the X-direction points in the length of the GPHE and Y-direction in the width of the GPHE. The vertical direction is denoted Z and has a positive direction upwards.

The only time other directions are used is in the calculations, where the Z-direction is positive in the opposite direction, downwards. This will be further explained in the verification section.

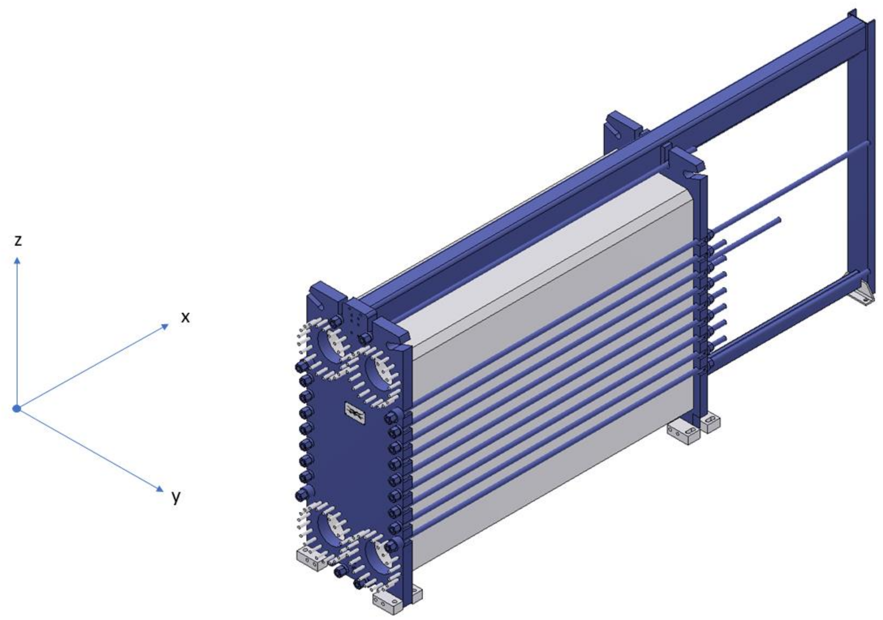


**Figure 3: Coordinate system used during this project.**

## 2.2 GPHE foot

The foot of a GPHE is the component that transfers the weight and loads from the GPHE to its foundation. The foot is attached to the frame plate or pressure plate with bolts, named plate bolts (PB), and connected to the ground with an anchor bolt (AB), as seen in Figure 4 below. Plate bolts extend through the feet and the attached plate and fastened with a nut on the other side. The anchor bolt is meant to be infused in the foundation where the GPHE is placed and protrude from the ground enough to fit through the foot and be attached with a nut on top of the foot.

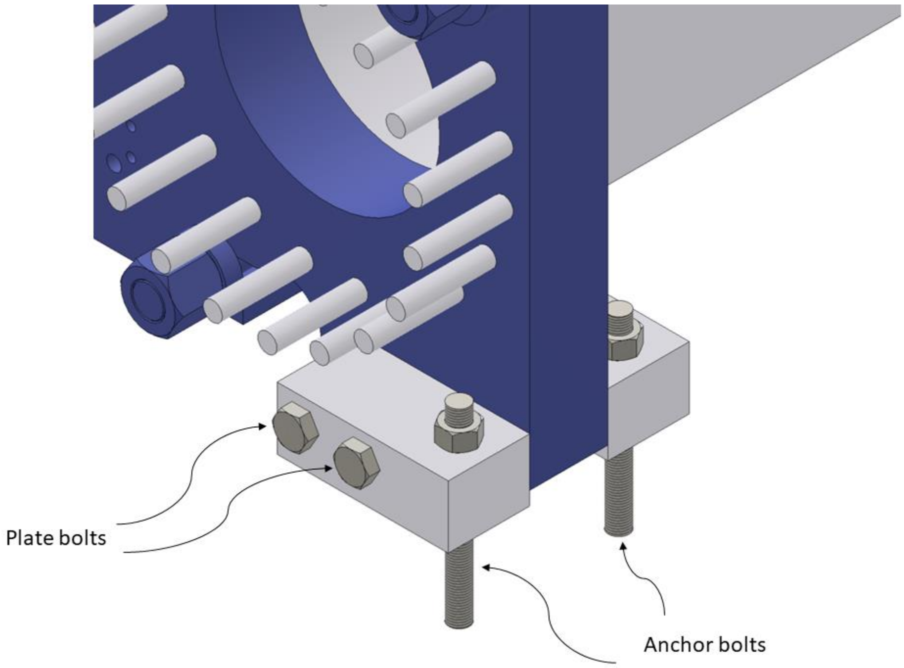


**Figure 4: Attachment of foot onto the frame plate.**

### 2.2.1 **Existing designs**

There are several foot sizes and designs to fit the various load demands and product sizes of GPHEs. The different designs of feet in the standard product range can be divided into two categories, reinforced- and standard feet. On top of this the feet can have different attachment principles which further divides them into different designs. Mainly two attachment principles are used, the swing principle and the compact principle. This gives four main designs that are used in today's GPHEs. Furthermore, feet are designated to either the FP or PP which creates two variants of every design. The different designs of feet are explained and elaborated more in the following subsections.

### *2.2.1.1 Reinforced feet*

For heavier loads, reinforced feet are most commonly used. The reinforcement comes from the fact that the foot is manufactured out of a solid chunk of metal and thus have a very rigid behaviour. The most common design of reinforced foot can be seen in Figure 5 below and is called a reinforced swing foot. Swing implies that it uses the mentioned swing attachment principle. The swing principle has the anchor bolt placed outside of the plate bolts, as seen in Figure 5. The swing principle is not only used on reinforced feet, but also standard feet. The principle merely describes the position of the plate bolt and anchor bolt holes in relation to each other. The swing principle creates a more serviceable GPHE as the foot can turn (swing) around the anchor bolt in a different manner.

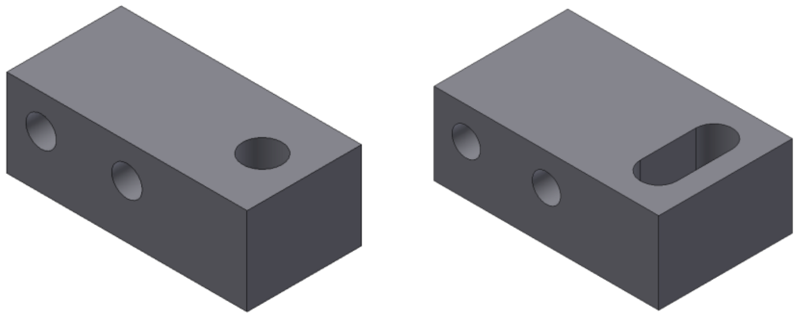

**Figure 5: Reinforced feet with the swing foot feature.**

The other design of reinforced feet uses the other attachment principle named compact but has similar characteristics otherwise. It is also manufactured through machining and drilling a solid block of metal into the desired shape. The attachment principle used in this design has the anchor bolt placed in between the plate bolts as seen in Figure 6 below. The compact reinforced foot is the older of the designs compared to the reinforced swing foot and is used rarely in today's products. It is used primarily on the largest model of GPHE, the T50. Calculations done to the two different reinforced designs shows that the bolts are more exposed to the applied loads in the swing foot. As the T50 is very large and heavy it has not been able to switch from the older compact principle to the new swing principle. Because of the width of the reinforced compact foot on T50 a chamfer has to be made in order for it to fit the appropriate flanges, as seen in Figure 6.

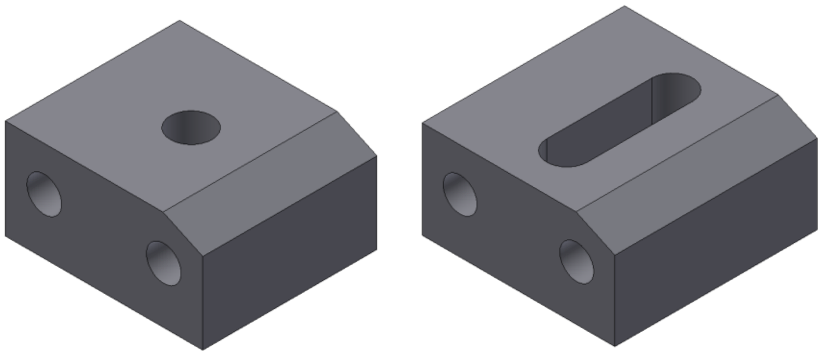

**Figure 6: Reinforced feet with the compact attachment principal, for the T50.**

Figure 5 and Figure 6 also shows the two different variants of each of the reinforced feet. The two variants exist due to the varying load and tolerance conditions at the different foot positions. Feet attached to the FP are slightly narrower in the X-direction of the GPHE and have a circular hole for the anchor bolt. Feet attached to the PP have a slot for the anchor bolt to compensate for the tolerances in the length of the GPHE. A GPHE can be several meters long and the combined tolerance in the length has to be considered when anchoring the GPHE. These differences between feet designated to FP and PP are general and used by all feet in the standard product range.

*2.2.1.2 Standard feet*

In occasions where the customer does not need reinforced feet, standard feet can be used. The standard feet are made from a L-profile with the holes or slot drilled out. Both previously described attachment principles are used to the standard feet as well, and therefore uses the same hole configuration. Two swing standard feet can be seen in Figure 7 below. The standard foot fills the same function as the reinforced foot, but with lower requirements for structural integrity as a consequence of less external loads.

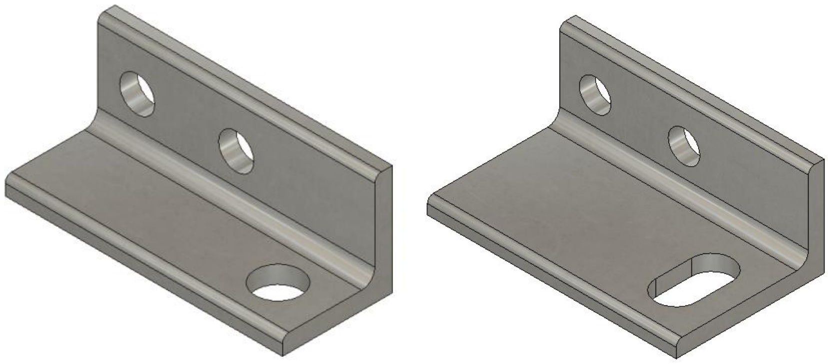

**Figure 7: The standard feet used in cases with lower loads.**

### 2.2.2 Bolts and bolt holes

Depending on the size of the GPHE and thus the size of the feet, different dimensions of bolts have to be used to attach the feet. Table 1 below shows the dimensions of bolts used in the products within this project scope. Alfa Laval does not supply the customer with the anchor bolt and thus only gives a recommendation regarding the anchor bolt.

**Table 1: Plate and anchor bolt dimensions for the different sizes of GPHE.**

| *Product* | *Plate bolt* | *Anchor bolt* |
|---|---|---|
| T35 – FD | M30 | M36 |
| T45 – FD | M39 | M42 |
| T50 – FD | M39 | M42 |

### 2.2.3 Ground Clearance

When the feet are attached, they keep the GPHE slightly above the ground, as can be seen in Figure 8. This is done to prevent damages on the coating of the FP and PP, and in turn minimise the risk of corrosion.

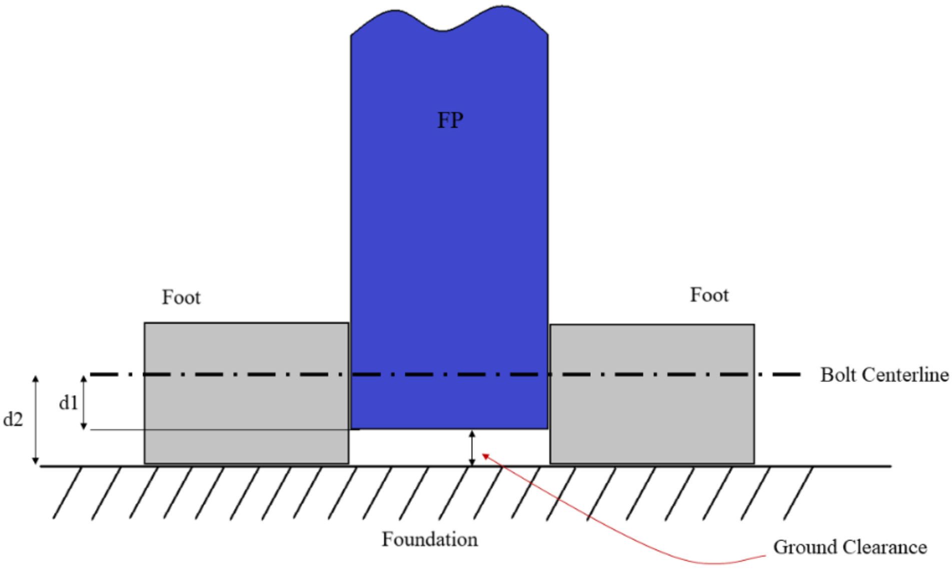


**Figure 8: Schematic of the ground clearance created by the feet.**

In general, the ground clearance aims to be 20 mm for all large GPHEs included in this project. In Table 2 the ground clearance for the included GPHEs is presented. It is determined as the difference between the vertical distance from the foundation to plate bolt hole of the foot, and the vertical distance between plate bolt hole and bottom edge on FP or PP.

**Table 2: Ground clearance data.**

| | | | |
|---|---|---|---|
| | | ***Frame Plate*** | |
| ***Product*** | ***d1*** | ***d2*** | ***Ground clearance*** |
| T35 | 37 mm | 56 mm | 19 mm |
| T45 | 47 mm | 67 mm | 20 mm |
| T50 | 57 mm | 67 mm | 10 mm |
| | | ***Pressure Plate*** | |
| ***Product*** | ***d1*** | ***d2*** | ***Ground clearance*** |
| T35 | 36 – 46 mm | 56 mm | 10 – 20 mm |
| T45 | 47 – 57 mm | 67 mm | 10 – 20 mm |
| T50 | 47 mm | 67 mm | 20 mm |

More recent products of GPHE have an oblong plate bolt holes in the PP to facilitate service when tolerances or deflection of the carrying bar (CB) has misaligned the plate bolt hole in the foot and PP. Therefore, the ground clearance can theoretically vary between 10 and 20 mm in these products. Older products can also have a smaller ground clearance as they were designed before the aim to have a 20 mm ground clearance was established.

### 2.2.4 **Feet Configuration and Service**

Feet can be configured differently depending on the size of the GPHE and its application. For lighter applications and smaller GPHEs, fewer feet can be used. The feet can then be configured with two feet on the FP and two feet on the PP. For the larger GPHEs that are included in this scope, the feet are configured with four feet to the FP and four feet to the PP as seen in Figure 9. When four feet are used on the PP, issues arise when the GPHE has to be opened during service. Service includes moving the PP backwards to expose the inner corrugated plates. The rear pair of feet and anchor bolt are blocking the PP from moving backwards and therefore the rear feet has to be moved out of the way. This function has been implemented in the swing foot principle mentioned earlier. As seen in Figure 9 the feet can be angled outwards as they are only anchored in one end point of the foot. This is also facilitated by the design of the PP that has a cut out in the bottom corners. In the older compact principle, the feet have to be lifted of the infused anchor bolt to move out of the way. Furthermore, a slot for the anchor bolt has to be made in the PP as the anchor bolt is positioned closer to the centre of the PP in the compact principle. These inconveniences in serviceability were the reason behind developing the swing attachment principle.

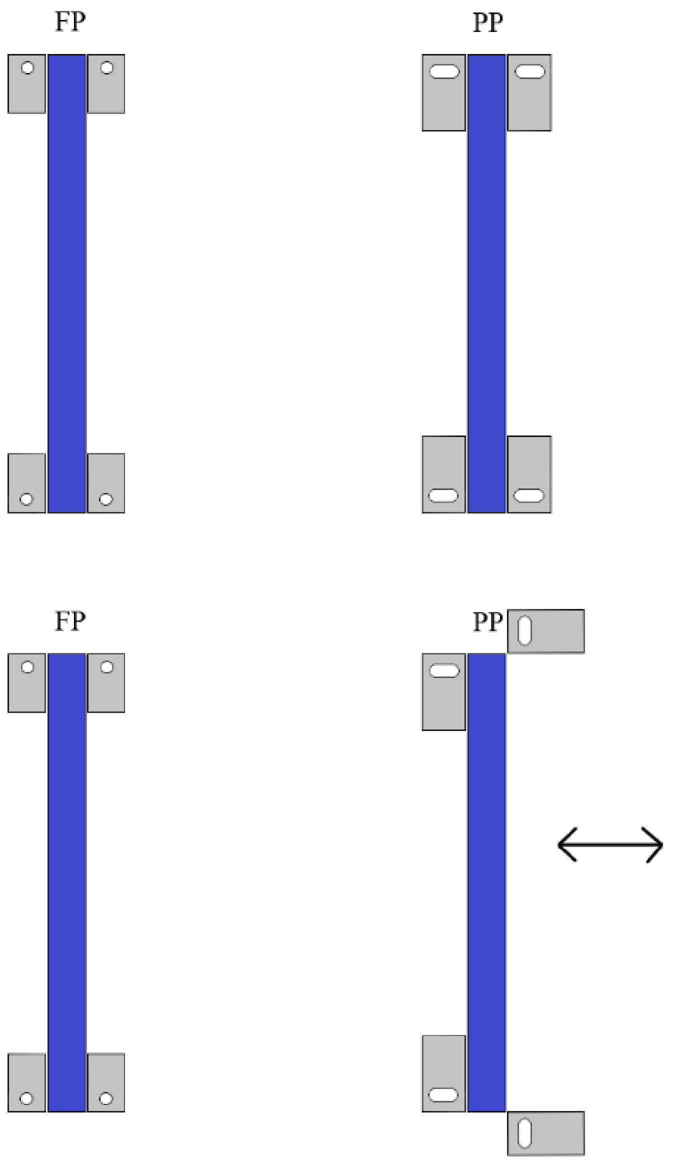


**Figure 9: Foot configuration with four feet on both FP and PP. Top image shows a GPHE in use while the bottom image shows a GPHE in service. The rear feet are moved out of the way using swing foot functionality.**

### 2.2.5 Material and Surface Finish

Reinforced feet are manufactured from a low alloy steel and standard feet are manufactured from unalloyed or low-alloy steel, all according to internal Alfa Laval standards.

Surface coatings on feet are also done according to internal Alfa Laval standards. The feet can be either painted, zinc coated or untreated, depending on the surrounding at the customer’s facility.

## 2.3 Related Components and Interference

There are several components in the near vicinity of the feet that can conflict with potential feet designs. The main components that risk to conflict with new designs are the pipe connection flange and the tightening bolts. In Figure 10 a pipe connection is assembled on a FP together with the feet to present the potential interference. It is important that new designs do not prevent any pipe connections or the assembling and disassembling of tightening bolts.

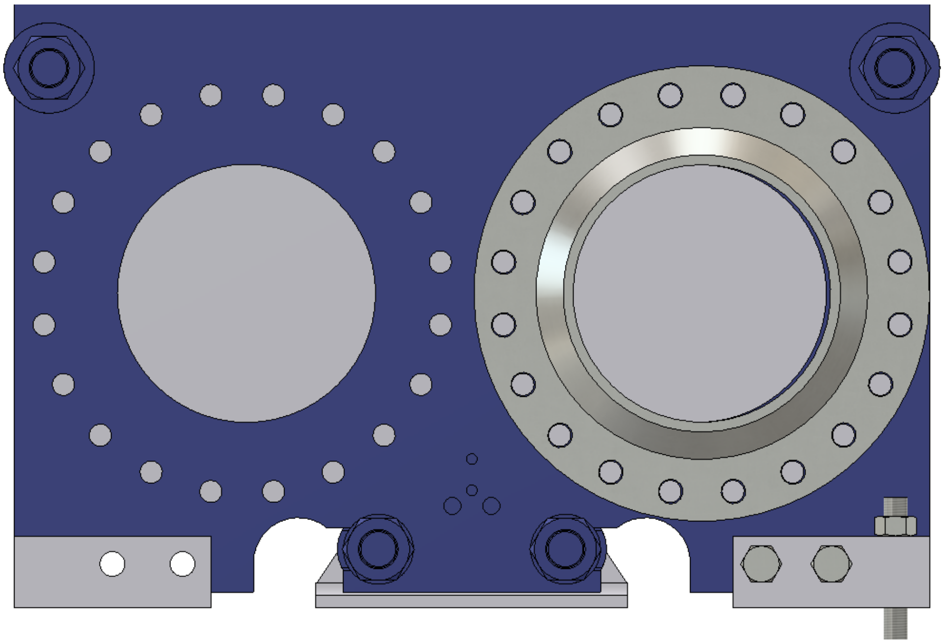

**Figure 10: GPHE with attached foot and pipe flange in the right port hole.**

Alfa Laval has seen potential issues with interfering before and has therefore introduced a design rule regarding feet. When using a design that includes fastening the anchor bolt with a nut on top of the foot, the vertical distance between the top of the foot and any connections has to be at least three times the height of the used nut as seen in Figure 11.

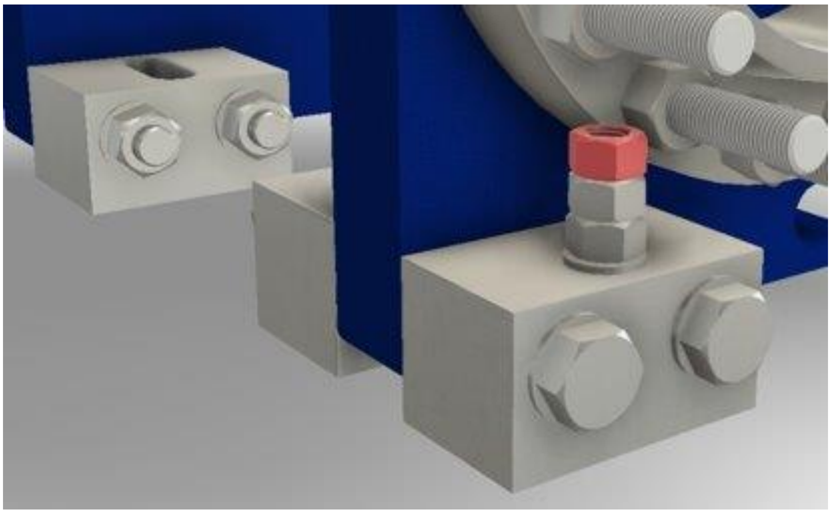

**Figure 11: Design rule to avoid interference between flange and assembly of foot. Note that the red nut is not used in reality and only shows the needed clearance.**

### 2.3.1 Frame- and Pressure Plate Thickness

Depending on the applications of the GPHE, it can be certified for different pressures. The design pressure of the GPHE affect its components like frame and pressure plate. Higher pressures demand thicker frame and pressure plates. In Table 3 below the different thicknesses and its relation to the GPHE model and pressure rating can be seen. Because feet can be attached to both sides of the plates, the plate thickness is important in feet designs. In Table 3 several pressure ratings are shown but the project focuses on the FD-rating which is the highest rating found in the concerned models.

**Table 3: Frame and pressure plate thicknesses for different products and pressure requirements.**

| *Product* | *Frame plate* | *Frame plate* |
|---|---|---|
| T45 – FM | 90 mm | 80 – 90 mm |
| T45 – FG | 100 – 115 mm | 80 – 105 mm |
| T45 – FD | 130 – 140 mm | 105 – 130 mm |
| T50 – FM | 90 mm | 90 mm |
| T50 – FG | 115 – 130 mm | 105 – 135 mm |
| T50 – FD | 145 – 170 mm | 145 – 170 mm |

### 2.3.2 **Flanges**

The ASME standard B16 chapter 5 describes, among other things, the dimensions, materials and tolerances of pipe flanges and fittings derived by the American Society of Mechanical Engineers. This is the standard that will be used as a template for the flanges during this project as they are the largest flanges compared to other standards used by Alfa Laval. In Table 4 the dimensions used in this project can be seen together with the related nominal pipe size and product. Class 300 pressure rating is used in this project.

**Table 4: Flange sizes according to ASME B16.5-2009 class 300.**

| ***Product*** | ***Nominal Pipe Size (NPS)*** | ***Outside flange diameter*** |
|---|---|---|
| T35 | 12” | 520 mm |
| | 14” | 585 mm |
| T45 | 18” | 710 mm |
| T50 | 20” | 775 mm |

## 2.4 Costs and Suppliers

Alfa Laval is a global company and has production in several countries. Manufacturing costs vary in different parts of the world and the location of manufacturing is important for the design. Table 5 below shows the share every region supplies. Included are all different kinds of feet for all product models in the project scope. The data was collected in collaboration with the purchase department at Alfa Laval. Presented data are excluding shipping from the underlaying costs.

**Table 5: Manufacturing quantity and shares for different supply regions, regarding feet in the project scope.**

| *Supplier Region* | *Received quantity* | *Share of total received quantity* | *Share of total order value* |
|---|---|---|---|
| China | 3522 | 66,89 % | 38 % |
| India | 913 | 17,34 % | 14 % |
| Brazil | 518 | 9,84 % | 20 % |
| Europe | 309 | 5,87 % | 27 % |
| Korea | 3 | 0,06 % | 0 % |
| USA | 0 | 0,00 % | 1 % |
| **TOTAL** | 5265 | 100,00 % | 100 % |

As seen in Table 5, about 2/3 of feet are produced in China. Second to China is India with just over 1/6 of total quantity. Costs are however not similarly distributed. China still represents the largest share of costs, but not as clearly as in quantity. Europe's relatively small quantity share is not trailing China by much in terms of costs, indicating a general greater manufacturing cost in Europe.

The costs were also broken down into the different feet articles from some of the suppliers. Prices were still excluding shipping and some suppliers have a minimum order quantity for certain articles, but to simplify the minimum order quantity has been neglected in this project. From the data it is apparent that the supplier in China is the cheapest manufacturer, India is second, and Sweden remarkably more expensive. Some suppliers do not manufacture all articles but the supplier in China do supply all articles in this scope.

To make the comparison between the different designs of feet more evident, Table 6 shows the relation between the costs. The table shows the relation between the average cost of the designs manufactured at the Chinese supplier. It shows that the reinforced swing foot is 3,38 times more expensive than the standard foot. The reinforced compact foot is 4,2 times more expensive than the standard foot. Further, the reinforced compact foot is 1,24 times more expensive than the reinforced swing foot.

**Table 6: Cost comparison between different feet designs manufactured in China.**

| | *Standard* | *Reinforced swing* | *Reinforced compact* |
|---|---|---|---|
| ***Standard*** | 1 | 3,38 | 4,20 |
| ***Reinforced swing*** | 0,30 | 1 | 1,24 |
| ***Reinforced compact*** | 0,24 | 0,81 | 1 |

## 2.5 External Loads

As mentioned in the problem description, GPHEs are exposed to various external loads. The external loads can be mild or severe depending on the application and surroundings. This project involves severe external loads that will be based on the standard API 662 Part 1 / ISO 15547-1. It describes, amongst other things, requirements, and recommendations for the mechanical design. The standard is applicable to heat exchangers used in the petroleum, petrochemical, and natural gas industry. Most relevant to this project are the specified loads given in the standard. As the project aims to design for severe external loads, table 2 in the standard will be used. It specifies force and torque loads acting on the connections of the heat exchanger to quantify the nozzle loads. In Figure 12 below the directions specified by the standard are presented.

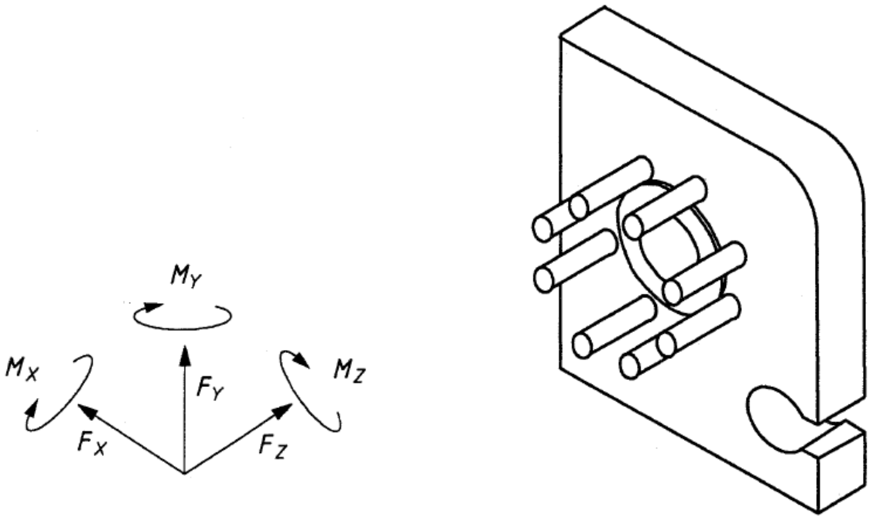


**Figure 12: Load directions specified by API 662 Part1 / ISO 15547-1.**

According to the standard, all loads are equal in the given directions, both forces and torques. The values of the loads depend on the size of the piping and are presented in Table 7 below.

**Table 7: Loads acting in the specified directions according to API 662.**

| ***DN*** | ***NPS*** | ***Force*** | ***Torque*** |
|---|---|---|---|
| 300 mm | 12” | 11 734 N | 15 280 Nm |
| 350 mm | 14” | 14 119 N | 20 539 Nm |
| 400 mm | 16” | 16 572 N | 26 665 Nm |
| 450 mm | 18” | 19 088 N | 33 711 Nm |
| 500 mm | 20” | 21 661 N | 41 732 Nm |

Additionally, Alfa Laval adds the force equivalent of an acceleration of 0,3g in the calculation and verification, on top of the loads described by API 662. This is to account for some seismic forces.

## 2.6 Design to Cost

Costs can be defined in different ways depending on the context. In economics, from a company perspective, costs can be defined as the monetary value of the resources a company consumes to produce its value. The consumed resources can be material as well as immaterial such as labour or information. Costs can in turn be divided into different levels depending on the cost's origin as seen in Figure 13. Costs directly related to the process of producing a product is named manufacturing costs. These costs include material and labour as well as any overhead costs included in the manufacturing process. When administrative costs are added to the manufacturing costs, it becomes the total costs. If costs related to the purchase, usage and disposal, costs usually inflicted on the customer, are included to the total costs, the aggregated costs become life cycle costs (Ehrleinspiel, Kiewert, Lindemann, 2007).

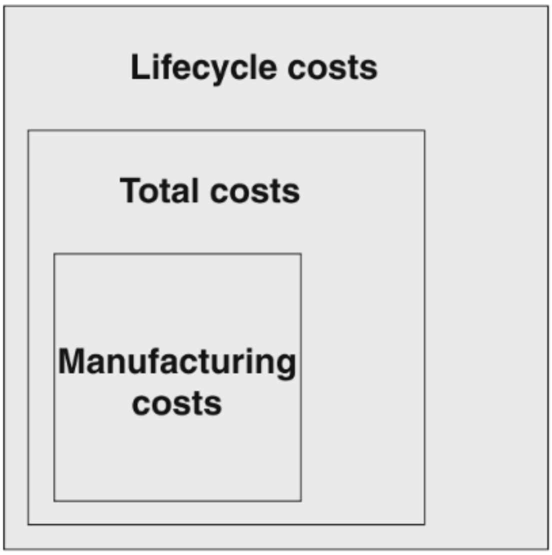


**Figure 13: The different levels of costs (Ehrleinspiel et al., 2007).**

One of the most important things to consider when trying to reduce costs within product development is to make changes early in the realisation process. Technical changes become increasingly more expensive during the realisation process, from the specification stage through the design stage and production planning. This exponential increase in cost through the stages has been specified by the "Rule of Ten", where the costs associated with technical changes increase tenfold with every stage. This implies that making changes in later stages of the realisation can be 100 or even 1000 times more expensive than making the changes in the first stages (Ehrleinspiel et al., 2007).

### 2.6.1 Reducing Manufacturing Costs

Manufacturing costs can generally be reduced by all departments of a company, although the product development and production departments have the largest impact. To successfully reduce costs for a product, good communication is key. A company can reduce its manufacturing cost for a specific product in several ways, but the possibilities can be divided in categories. In Figure 14 below the strategies for cost reduction according to Ehrleinspiel, Kiewert and Lindemann, (2007) can be seen.

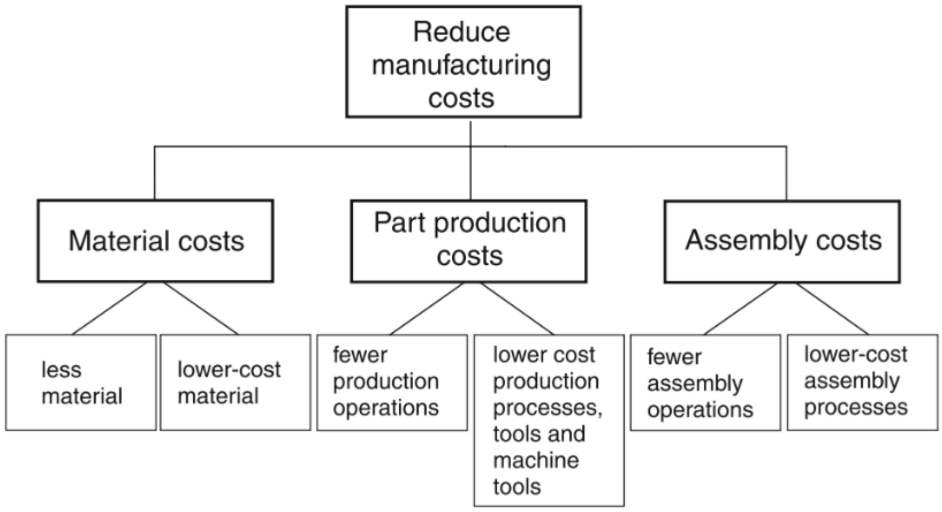


**Figure 14: The different ways of reducing manufacturing costs (Ehrleinspiel et al., 2007).**

The manufacturing cost reduction begins before the actual design process, with the creation of requirements for the product. As more demands are inflicted onto the desired product, it becomes more expensive. In this part of the development process, it is important to keep the requirements to a minimum to not over-constrain the product and create unnecessary costs (Ehrleinspiel et al., 2007).

During the conceptual and design phases of product development other things become important. First, the complexity and number of parts in a product usually increase the costs. Because of this, the designer should keep in mind that overly complex concepts are not beneficial from an economical perspective (Ehrleinspiel et al., 2007). The idea of keeping the design simple and easily interpreted is also highlighted by Sundström, Bjärnemo and Andersson (2000), as simplicity is described as one of the core rules in design engineering. According to them, simplicity is described as using as few parts as possible and having a logical interaction between parts and functions. On a part level, fulfilling the rule of simplicity should be done by using simple geometric shapes and symmetry in parts. This will make manufacturing easier and thereby making it cheaper. Simple geometries prevent time-consuming tooling changes and operations.

## 2.7 Bolted Joints

Bolted joints have a requisite preload to function properly. Aspects affecting the requisite preload are the load magnitude and direction, elasticity in bolt and joined parts, settlements, and the point of attack of the load.

The maximum allowed preload in a bolt is given by the equation below according to Colly Components (1995).

$$F_a = \sigma_t \cdot A_t = K_p \cdot v \cdot R_{eL} \cdot A_t \tag{2.1}$$

$K_p$ is a correctional factor and is usually in the range of 0,6 to 0,8. The variable $v$ is the factor at which the bolt can be used relative its yield point. It varies in the range from 0,5 to 0,9 depending on the surroundings but it is often assumed to be 0,9. $R_{eL}$ is the yield point of the bolt and $A_t$ the tensional area of the bolt.

European Committee for Standardization (2005) simplifies the preload in designing slip resistant bolted connections in Eurocode 3 according to equation (2.2) below.

$$F_{p,C} = 0{,}7 \cdot f_{ub} \cdot A_s \tag{2.2}$$

In (2.2) the preload $F_{p,C}$, is dependent on the ultimate strength $f_{ub}$, and the tensional area $A_s$.

Eurocode 3 further dictates several frictional coefficients (slip factors) for different types of surfaces. The values can be seen in Table 8 below.

**Table 8: Frictional coefficients according to Eurocode 3.**

| ***Surface treatment*** | ***Frictional coefficient*** |
|---|---|
| Blasted surfaces without rust | 0,5 |
| Blasted surfaces with metal sprayed coating or zinc coating | 0,4 |
| Surfaces cleaned with metal brush without rust | 0,3 |
| Rolled metal surfaces | 0,2 |

## 2.8 General Solid Mechanics

Following are equations related to basic solid mechanics used in the project. All equations are gathered from Instutitionen för Hållfasthetslära KTH (2014).

$$\sigma = \frac{F}{A} \tag{2.3}$$

$$\sigma = \epsilon E \tag{2.4}$$

$$\epsilon = \frac{\delta}{L} \tag{2.5}$$

$$S = \frac{F}{\delta} \tag{2.6}$$

In the equations, $\sigma$ is the tensile stress calculated as the force *F*, divided by the area *A*. The stress is also given as the multiplication of the strain $\epsilon$, and the Young's modulus *E*. The strain is in turn given by the ratio between the displacement $\delta$, and the initial length *L*. Stiffness *S*, is the ratio between the applied force and the displacement.

# 3 Methodology

## 3.1 General

The methodology throughout this project will be based on the generic development process described by Karl T. Ulrich and Steven D. Eppinger. It will also take in aspects of the design process used at Alfa Laval including a design review. Furthermore, the working procedure will constantly aim to use the philosophy from concurrent engineering in order to develop a more implementable product.

## 3.2 Ulrich and Eppinger Methodology

Ulrich and Eppinger (2012) conclude that a development process is the flow of activities that is used to realise ideas into actual products. As the project is aimed to develop a new or refined component based on a vision from a company, the process from Ulrich and Eppinger (2012) is deemed a good choice to base the methodology on. The development process in this project will neglect some parts of the Ulrich and Eppinger (U&E) process to better fit the product and the resources available in the project, as described further on.

According to U&E, the generic development process can be divided into six steps or actions and is displayed by Figure 15 below.

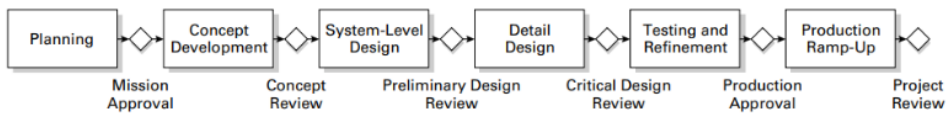


**Figure 15: The steps in the product development process (Ulrich and Eppinger, 2012).**

This project will focus on concept development and its underlying activities including the seven steps seen in Figure 16. These activities and its implementation in this project are further explained in the upcoming sub-sections.

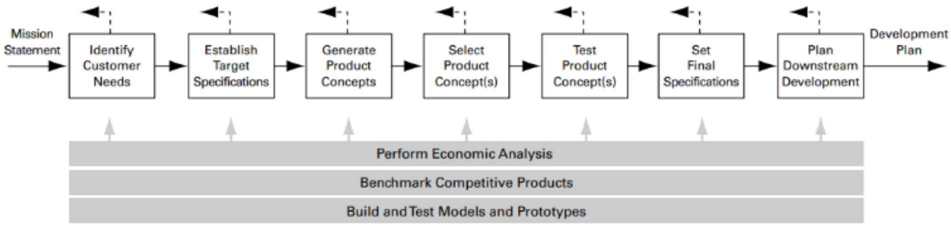


**Figure 16: The underlying activities in concept development according to Ulrich and Eppinger (2012).**

### 3.2.1 **Identifying Customer Needs**

The idea of identifying customer needs is to create a communication between the end user and the project to get information about what the end user requires. According to Ulrich and Eppinger (2012) needs are mostly disconnected from the product itself and should focus more on the customer's situation. Other definitions of needs exist. For example, within marketing, needs are described as the most basic form of felt deprivation and can be divided into several levels depending on the type. When the customer is influenced by the surroundings, needs are instead named wants (Kotler, Armstrong, Parment, 2020). During this project, however, needs and wants will be considered the same and rather differentiated by its importance.

The working procedure in identifying customer needs will be guided by the steps from Ulrich and Eppinger (2012). These steps are made to ensure that not only obvious needs are identified, but also latent and hidden needs. As the product of this project is aimed towards other businesses, and the possibility to meet and gather information from the customers is severely limited, these steps are modified. The data will be gathered from internal resources and people working closely to the end customer instead of gathering the data directly from the customer. The steps in this part of the development process are the following:

1. Gather raw data from service and other people working closely to the end customer.
2. Interpret the raw data in terms of customer needs.
3. Establish the relative importance of the needs.

### 3.2.2 **Establish Product Specifications**

Customer needs tend to be oriented from a customer's perspective and the translation to specifications facilitates the work made by designers to create viable concepts. According to Ulrich and Eppinger (2012), product specifications should be established at least twice during the development process. Once directly after the customer needs have been identified and once after a product concept has been selected. The first set of specifications is named the *target specifications* as these specifications are viewed as the goal for the product. The second set of specifications is a revised version of the target specifications made when the development team has more accurate data regarding the concept's characteristics. At that point, correlation between parameters have become apparent and trade-offs have to be made. The refined specifications are called the *final specifications*. Due to limitations in physical testing and the time available in this project, the final specifications will not be specified.

To conduct the first step in the process, to prepare the list of metrics, the development team has to translate the customer needs into measurable metrics. The idea is to relate the metrics and needs to the extent were fulfilling the set-out metric corresponds to satisfying the customer need completely. Ideally every need has one single metric, but in practice two or more are acceptable.

The collection of benchmarking information is an important step in the establishment of product specifications, as it creates a reference for the design team. However, benchmarking is also very time consuming and requires access to competitive products (Ulrich and Eppinger, 2012). During this project, access to benchmarking information is limited because the competitive products are not available to the public. Neither does the company have information about competitive products. Therefore, benchmarking is only done regarding the current products of Alfa Laval through the verification.

The steps included in the establishment of product specifications are:

1. Prepare the list of metrics.
2. Collect benchmarking information from within Alfa Laval.
3. Set ideal and marginally acceptable target values.

### 3.2.3 Generate Product Concepts

The majority of the steps in the generation of product concepts are derived from the U&E methodology. The first step in this process is to clarify the problem. In U&E it is suggested that the development team creates a general understanding of the problem and if necessary, breaks it down into smaller subproblems. The process of breaking up a complex problem into smaller subproblems is called problem decomposition. The decomposition can be done in many ways and is usually a good way of approaching a concept development process. Problems can be decomposed regarding for example function.

The second step taken in this process is to search externally. Examples of external search can be to interview lead users or experts on the topical area. Lead users tend to see issues with the product at a much earlier stage and can therefore contribute with valuable information on how to improve current products. Experts might already have some answers or solutions to the subproblems the development team tries to solve. According to Ulrich and Eppinger (2012), patent search is also a good way of investigating the already existing solutions to the problems the development team are facing. Patents newer than generally 20 years are usually protected. The protection indicates that companies who wishes to use the patented solution has to compensate the owner. Because of this the patent search process might result in limitations instead of opportunities. However, patents can also work as an inspiration to new concepts, but the development team has to make sure not to infringe on the existing patent.

The third step in concept generation is to do internal searches. Internal search means to explore the knowledge already existing in the development team. There are several ways to induce the latent ideas inside the team, where brainstorming might be the most common. Brainstorming can be done both individually and in group sessions. There are several important things to keep in mind during brainstorming to optimize the flow of ideas. First, it is important to suspend all judgement. In practice this means that during sessions, criticism is prohibited. Potential weaknesses in concepts have to be lifted in terms of new suggestions. Concepts that seem infeasible from the start can be very valuable as they expand the team's view of possible solutions. It is also beneficial to produce a maximum number of ideas. The focus on quantity lowers the expectations for quality which in turn can open up for more creativity. Every generated concept stimulates new thought processes and will because of this enhance the creativity. During the brainstorming sessions it is also encouraged to use graphical and physical media. Different ways of expressing one's ideas can improve creativity and understanding in the team (Ulrich and Eppinger (2012). To conclude, the steps that will be taken in the concept generation phase are the following:

1. Clarify the problem.
2. Search externally.
3. Search internally.
4. Reflect on the results and process.

### 3.2.4 **Concept Selection**

The selection process used in this project is based on the method *Concept scoring* from Ulrich and Eppinger (2012). In this process the first step is to make a selection matrix with criteria based on the customer needs and specifications. The criteria are also weighted according to its importance.

When the matrix is complete the concepts is scored on a scale ranging from 1-5 where five is the highest score.

## 3.3 In-depth Development and Design Review

The in-depth development and design review are steps in the development process used at Alfa Laval. In the in-depth development, the proceeding concepts are further concretised to investigate the possibilities of implementation. The idea with the design review is to present the project process, results and decisions to a wide team of engineers to raise potential issues. In this way future potential problems can be found early and rectified.

## 3.4 Concept Verification

As all physical testing and prototyping is unavailable, verification will be carried out in simulation and with basic calculations. Software such as ANSYS Workbench will be the most prominent. Testing will be done by first setting a reference with some of the already existing products and later comparing the results to the selected concept.

## 3.5 Concurrent Engineering

Concurrent engineering is not considered an actual methodology but rather a way of thinking. The philosophy is to integrate several areas of a corporation, marketing, manufacturing, logistics, customer support and so on, into the product and concept development process. By doing this, different aspects of the product's life cycle are considered already in early stages of a product. The goal is to reach a higher productivity and lower costs by shortening the development time and the time-to-market. Implementing concurrent engineering is usually a long process as it requires a wide range of skills from both technical and organisational. Key in reaching a parallel workflow is the communication between the different departments within a company (Stjepandic, Wognum, Verhagen, 2015).

In this project, the concurrent engineering process will be implemented to the best possible extent. Practically this means to keep a communication between several departments within the company to try to find a solution that best suits all stake holders.

# 4 Identifying Customer Needs and Product Specifications

## 4.1 Defining stakeholders

- **End Users:** End users of Alfa Laval's products are essentially the customers of Alfa Laval since distributors and intermediaries are rarely used. Customers purchasing the large industry-line of GPHEs are usually actors within the oil and gas industry, heating, ventilation, and air conditioning (HVAC) applications, or other large scale process industry.
- **Service Personnel:** Alfa Laval's products are meant to be serviced regularly. The service personnel's task is to clean, exchange parts and make sure the GPHE is working properly.
- **Assembly department:** The department within Alfa Laval that assembles the GPHEs.
- **Suppliers:** The suppliers of parts needed to manufacture the GPHEs.

## 4.2 Interviews

Interviews conducted in order to identify the customer needs were held with people working closely with the product or in close contact with the end user. The approach in the interviews was to have about 10 predefined questions in the relevant topics for the interviewee. Some questions remained the same in several interviews while some were exchanged to better suit the expertise of the interviewee. During the interviews the interviewee was allowed to speak freely and touch upon other subjects in order to possibly find latent needs. The answers were then noted and summarised in a free-flowing text. These summaries are presented in the sub-sections below.

### 4.2.1 Interview 1 - Product Expert

During the phase of the project where customer needs where investigated, an interview with a Senior Global Product Expert was conducted. The product expert has 20 years of experience within the company and has worked in field engineering, sales, and aftermarket services. The current role includes troubleshooting installed GPHEs and managing services. As the product expert has a solid experience within service and meeting customers, the interview was aimed at defining the perspective of the customer and service technicians. Questions revolved around the impact of feet design in customers buying decision and how service personnel experience working with today's GPHEs and especially the feet of GPHEs.

The interview concluded that customers rarely take notice of GPHE feet and do not base any buying decisions on how the feet are designed or function. Most importantly for the customer is that the GPHE fulfils the customers' needs regarding heat transfer and capacity. However, if the GPHE cannot operate under the given circumstances due to the design of the feet, it will be discarded in the purchase process. From a customer perspective the feet only function as the support for the GPHE. Because of this, customers appreciate the simplicity and durability of feet in GPHEs. The product expert also emphasises that many customers have a scarce space around the GPHEs, something that can limit access to the feet and the ability to service them. The product expert explains that during a service, a specialised jack is used to lift the PP. This removes some load of the feet and the plate bolts in the feet can then be removed. Depending on the design of the foot, there are different ways to remove it. The swing foot model can be angled 90 degrees away from the PP and then become free from the PP. The compact foot model has to be lifted of the anchor bolt in order to be removed and not be in the way of the PP. When the feet on the back side of the PP have been removed, the PP can be pushed along the CB to expose the channel plates. Then the service on the channel plates and gaskets can be conducted. The product expert believes that the benefits of not having to lift the swing foot is not that great. According to him, service personnel do not make a difference between the two attachment principles. Equipment used to loosen and tightening bolts during service are the tools provided by the site. This usually includes a striking box wrench and a hammer for the larger GPHEs.

### 4.2.2 Interview 2 - Product Managers

To further widen the perspective of how the design of feet for GPHEs affect customers, an interview with two product managers was carried out. Also participating on the interview was a future product manager, currently a senior development engineer. The product managers had responsibilities for large GPHEs and GPHE extras, respectively. Extras include all components around the actual GPHEs, such as feet and connections etc. Questions in this interview where more focused on the customer and market perspective, rather than the service.

It was concluded during the conversation that the major challenges within the large segment of GPHEs were connected to documentation as the products tend to be very complex at the large scale. Some applications at the customer, such as nuclear energy production, require very extensive documentation of manufacturing and selected material for safety reasons. The dominating industry among customers of the large GPHEs, the oil and gas industry, requires the products to manage external loads as a product of the nozzle loads during operation. Other customers that operate in areas with high seismic activity requires the GPHEs to manage the external loads induced by a potential earthquake.

The most important things to keep in mind when developing a new foot according to the product managers were to make sure it can sustain the set-out loads and to keep the cost down.

During the interview it was clarified that Alfa Laval is not responsible for the anchoring of the GPHE to its foundation. Alfa Laval provides the GPHE with feet and a strongly suggested method of how to anchor them. This suggested method uses the bolt dimensions and articles verified by Alfa Laval to have the sufficient structural integrity to withstand the external loads. Earlier, issues have arisen when the specification of position and length of the anchor bolt have been insufficient. Customers have then had troubles opening and servicing the GPHE due to the wrong placement or length of the anchor bolt.

The product managers also lifted issues with a previous configuration system that did not have a thorough explanation for when external loads are relevant and when reinforced feet were not applicable. This resulted in a high demand for reinforced feet and issues when the reinforced feet could not be fitted due to space limitations. The limited space usually appeared when the GPHE consisted of few channel plates and the distance between the FP and PP became small.

### 4.2.3 Interview 3 - Senior Development Engineer, EPD

The interview with the senior development engineer was focused on the design perspective of feet. It aimed at identifying issues and potential solutions for existing designs of feet. The engineer works within existing product development and has approximately 40 years of experience within Alfa Laval. The interview was also conducted in order to try to catch some of the experience regarding how to tackle the problems of the project.

It was concluded during the interview that cost is the most important factor when designing feet or similar “simple” products. The engineer also explained that cost tend to be the most important part in deciding upon what design to develop and implement. To reach a successful design with low costs you want to avoid introducing new manufacturing techniques and new complex parts. Regarding GPHEs and feet in particular, the engineer believes that it is important to find a design that does not protrude outside the perimeter of the GPHE. He has found that often space around GPHEs can be very limited. When asked if supporting the GPHE from underneath can be an alternative in a new design, the engineer saw no apparent issues. He believed it to be an intriguing idea that should be investigated. A discussion regarding the bolted connection also arose, where the impact of the preloaded bolts and the friction in the joint were contemplated. He also mentioned that many facilities where the GPHEs are positioned, has a dedicated service team. The tools they obtain should be sufficient in many more advanced service applications.

### 4.2.4 Interview 4 - Service Site Facility Manager

The interview with the service facility manager aimed at clarifying the procedure of servicing large GPHEs. At the service facility in question, service of T45 and T50 is conducted. The manager explained that the service they do is conducted at a specific building and hence GPHEs have to be moved from its usual place to the facility building. When moving the GPHE, service technicians remove the anchoring (nuts connected to anchor bolt) and lifts the entire GPHE onto a trailer using a crane. The trailer with the GPHE is then driven to the service facility building where the actual service can be conducted.

During service, the facility manager underlines a few issues he has experienced regarding the feet. When removing the plate bolts for the feet, the weight of the PP can prevent the loosening of the bolts. In order to solve this, service personnel have to slightly lift the PP and thus removing the tension from the plate bolts. The same issue arises in the opposite manner when service personnel try to insert the plate bolts again to assemble the feet. The holes in the feet and holes in the PP are misaligned to the extent where the PP has to be lifted again to insert the bolts. The lifting of the PP is done with a specialised jack that fits the narrow gap underneath the PP. The facility manager emphasised that this is not a preferred way of working and the service personnel do not want to use a jack to assemble and disassemble the plate bolts. There is no designated place to position the jack when lifting and there is usually limited space around the GPHE. Apart from the jack, mainly manual tools are used, such as spanners, to dismantle the feet.

The service manager also raised an issue with the levelling of the GPHE. As it is crucial during assembly of GPHEs that it is level, he wanted to see some kind of levelling indicator built in to the GPHE. This can be either in the feet or in the rest of the frame.

### 4.2.5 Interview 5 - Senior Development Engineer, NPD

The second interview with a senior development engineer was also aimed at identifying issues with today's designs and finding interesting approaches for new designs. The engineer works within new product development and has approximately 20 years of experience within Alfa Laval.

The interview concluded that the most important thing when trying to find a new design to components such as feet, is the cost. The cost together with achieving the set out structural requirements should be the main focus in an evaluation of designs. Another main challenge in finding and implementing new designs is to make them work globally. Different countries and parts of the world have different design standards and means of manufacturing. This also makes cost calculations difficult as they can vary a lot from site to site.

The engineer mentions that he believed that the weakest link in existing designs was the plate bolts during an upward facing force on the GPHE. He believed it would induce high shear loads that cut the plate bolts similar to a scissor. Mostly due to the long lever between anchor bolts and plate bolts of the swing foot principle.

The engineer further explains that Alfa Laval's GPHEs are raised from the ground to prevent corrosion. Vibrations in the GPHE can quickly wear down the surface treatment on the underside of the frame plate and thereby enable corrosion. The products are also often placed outside, exposed to the weather, and water can flood the foundation of the GPHE.

## 4.3 Customer Needs

From the information gathered in the background and theory section and information collected during the above summarised interviews, a table of customer needs was assembled, see Table 9. It summarises the needs and requirements from both the company's and supposed customer's perspective. Each need was rated on its relative importance, and a note was made from where the need was derived from. The need could be explicitly pointed out or interpreted from the conversation during the interview.

**Table 9: Customer needs with its corresponding relative importance.**

| *No.* | *Customer need* | *Relative importance* | *Derived from* [a] |
|---|---|---|---|
| 1 | The foot can sustain the weight of a large GPHE | 5 | PS |
| 2 | The foot can sustain external loads | 5 | PS |
| 3 | The foot is cost efficient | 4 | I2, I3, I5 |
| 4 | The foot gits inside the dimensions of the FP and PP | 3 | I1, I3 |
| 5 | The foot can easily be removed and assembled during service | 4 | PS |
| 6 | The foot can be assembled despite deflection of CB | 4 | I1, I4 |
| 7 | The foot can be assembled and disassembled with simple tools | 3 | I1, I4 |
| 8 | The foot can be removed without lifting it | 2 | I1 |
| 9 | The foot can withstand a harsh outside environment | 4 | I1, I5 |
| 10 | The foot can be modularised to fit other sizes of GPHE | 4 | D |
| 11 | The foot is easy to document during manufacturing | 3 | I2 |
| 12 | The foot is anchored in a well-defined way | 3 | I2 |
| 13 | The foot keeps the GPHE at an exact height above ground | 4 | D |

[a] *PS – Product Specification, I1-5 – Interview 1-5, D – Deduced*

Based on the theory regarding requirements and specifications in development projects, the number of needs have been intentionally kept low. Few needs were considered positive to not over constraint the design and to try to keep an open mind during the concept generation phase.

## 4.4 Target Specification

To quantify the needs a table of target specifications was set up. The table can be seen below, Table 10, and displays the intended need to quantify together with a marginal and ideal value. Since no physical benchmarking could be conducted, many metrics are non-numerical and based on the experience of the engineers involved in the project. Metric 1 and 2 was tested in a simulation that gave guidance in how well it would sustain the loads in the real world. Costs was estimated since no deep cost analysis could be performed due to time- and resource shortage.

**Table 10: The target specifications derived from the customer needs.**

| ***No.*** | ***Corresp. need nos.*** | ***Metric*** | ***Relative importance*** | ***Marginal Value*** | ***Ideal value*** | ***Unit*** |
|---|---|---|---|---|---|---|
| 1 | 1 | The foot withstands the dead weight of the GPHE | 5 | Yes | Yes | Yes/No |
| 2 | 2 | The foot withstands loads described by API 662 Tab2 + 0,3g | 5 | Yes | Yes | Yes/No |
| 3 | 3 | Relative cost to today's alternative | 4 | 1,5 | Min | - |
| 4 | 4 | Width of foot outside PP | 3 | 50 | 0 | mm |
| 5 | 5, 7 | Number of tools needed to mount/dismount foot | 4 | 3 | 1 | Pcs |
| 6 | 6 | Height deflection tolerable | 4 | Yes | Yes | Yes/No |
| 7 | 5, 8 | Lifting of foot required during service | 2 | Yes | No | Yes/No |
| 8 | 9 | Current or equivalent surface treatment applicable | 4 | Yes | Yes | Yes/No |
| 9 | 10 | Scaling of design possible | 4 | Yes | Yes | Yes/No |
| 10 | 11, 12 | Detailed instructions regarding manufacturing and anchoring | 3 | No | Yes | Yes/No |
| 11 | 13 | Induced ground clearance | 4 | 18 | 20 | mm |

## 4.5 Needs-Metric matrix

To present the relations between the needs and the target specification metrics more intuitively, a needs-metric matrix was assembled. It can be seen in Figure 17 below where connected need and metric is portraited with a dot. The matrix displays that some metrics serves several needs, and one need has two metrics.

**Needs-Metric matrix**

| | **No.** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Metric** | The foot withstands the dead weight of the GPHE | The foot withstands loads described by API662 Tab2 + 0,3G | Relative cost to todays alternative | Width of foot outside PP | Number of tools needed to mount/dismount foot | Height deflection tolerable | Lifting of foot required during mount/dissmount | Current surface treatment applicable | Scaling of design applicable | Specific instructions regarding manufacturing and anchoring | Induced ground clearance |
| **No.** | **Need** | | | | | | | | | | | |
| 1 | The foot can sustain the weight of a large GPHE | • | | | | | | | | | | |
| 2 | The foot can sustain external loads | | • | | | | | | | | | |
| 3 | The foot is cost efficient | | | • | | | | | | | | |
| 4 | The foot fits inside the dimensions of the FP and PP | | | | • | | | | | | | |
| 5 | The foot can easily be removed and assembled during service | | | | | • | | • | | | | |
| 6 | The foot can be assembled despite deflection of CB | | | | | | • | | | | | |
| 7 | The foot can be assembled and disassembled with simple tools | | | | | • | | | | | | |
| 8 | The foot can be removed without lifting it | | | | | | | • | | | | |
| 9 | The foot can withstand a harsh outside environment | | | | | | | | • | | | |
| 10 | The foot can be modularised to fit other sizes of GPHE | | | | | | | | | • | | |
| 11 | The foot is easy to document during manufacturing | | | | | | | | | | • | |
| 12 | The foot is anchored in a well-defined way | | | | | | | | | | • | |
| 13 | The foot keeps the GPHE at an exact height above ground | | | | | | | | | | | • |

**Figure 17: Needs-Metric matrix showing the relation between the needs and the metrics in the target specification.**

# 5 Concept Development

## 5.1 Problem Decomposition

During the initial stages of the concept development, it was concluded that the objective of the foot could be divided into two sub-objectives. Firstly, the foot needed to support and attach to the frame- or pressure plate. Secondly, the foot needed to transfer the loads into the foundation and remain stationary. In short, the two sub-problems were attaching the foot to the plate and attaching the foot to its foundation.

## 5.2 Patents & Invention Requests

To explore the possibilities and define obstacles for the new design of feet, it was desirable to investigate potential patents in the related field. Contact was established with a specialised department at Alfa Laval that is dedicated to handling patents and the legal work related to new inventions. The employees at the patent department sent a list of patents that could affect the development of a new design. Although, it was concluded that none of the investigated patents would prevent the development, as very few patents of appropriate designs of feet could be found. Various pillar like feet and feet including a feature to adjust the height of the foot was found. All were deemed unfit for a GPHE and thus would not interfere with the development of a new foot design for GPHEs.

Together with the above-mentioned patents, the patent department also contributed with a list of invention requests from within Alfa Laval. These requests are ideas for inventions from employees of Alfa Laval that either have been investigated or are currently being investigated in order to become actual patents. These invention requests were used as inspiration in the upcoming concept generation.

## 5.3 External search

Apart from the patent investigation, the external research covered searching for mechanical solutions to retain heavy objects in other applications. Foundation solutions in bridges, stairs and walkways were used as inspiration, but also other industrial equipment as seen in Figure 18 where I-beams support a metal cabinet.

**Figure 18: Industrial equipment supported by I-beams (Photo: Daniel Rundstöm).**

Many of these foundations and joints used standardised beams and sections. In Figure 19 two I-beams are bolted to each other in a 90-degree angle with an additional square section beam. These joints inspired to try to find standardised solutions that can be bolted together.

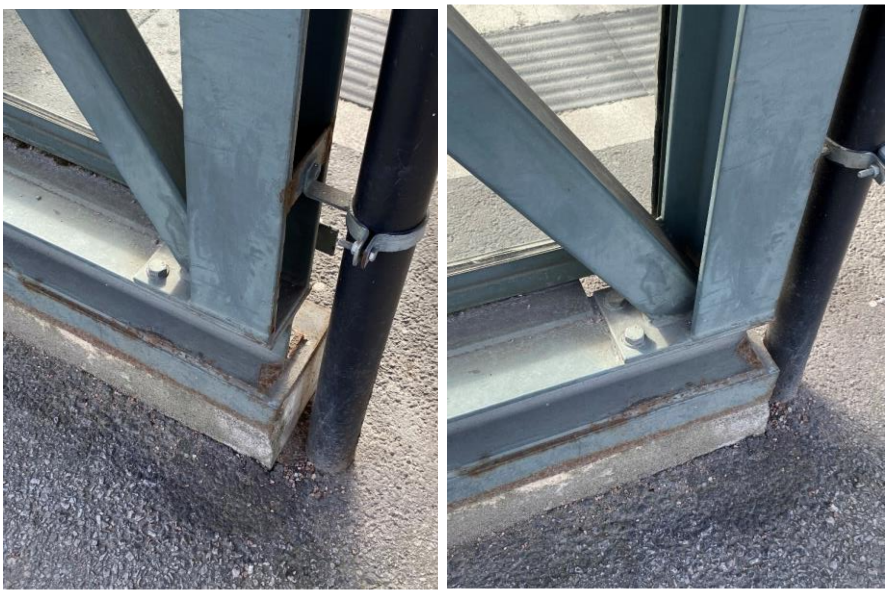

**Figure 19: Two joined I-beams with a hollow square section beam (Photo: Daniel Rundström).**

In Figure 20 a bolted support of a balcony can be seen. This shows an alternative in how to support large loads with a 90-degree load distribution. The joint itself uses plates instead of standardised beams and sections.

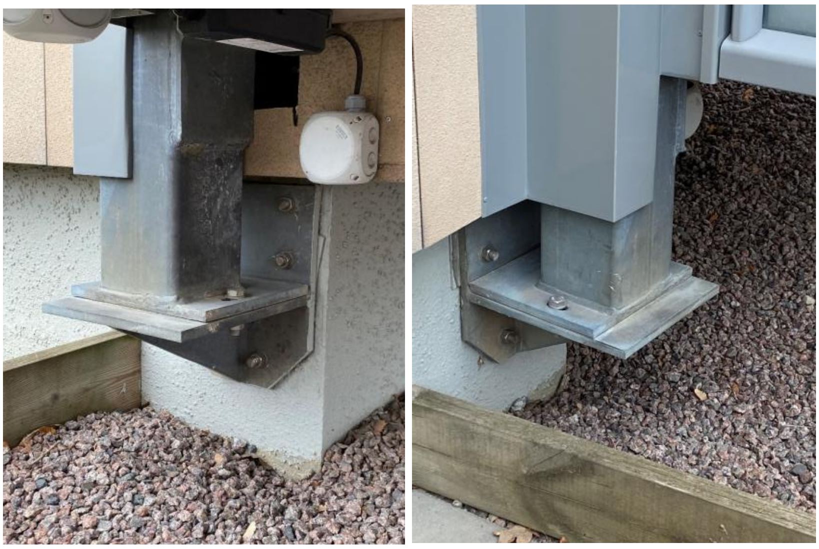

**Figure 20: Support for a balcony (Photo: Daniel Rundström).**

Figure 21 shows inspiration to a 45-degree joint between two U-beams. These kinds of joints could be applicable in a support for heavy equipment.

**Figure 21: Two joined U-beams in a close to 45-degree angle (Photo: Daniel Rundström).**

## 5.4 Concept Generation Session

The concept generation session was conducted by a group of five engineers or engineering students. The group consisted of a thermal analyst, a development engineer within channel plates, a project leader and former conceptual engineer, and two engineering students doing their master thesis at Alfa Laval. The chosen members had different backgrounds and little to no knowledge of feet in GPHEs, in order to enter the session without any prejudice. The different backgrounds were meant to contribute with a variety of reflections and a broader mind. This was considered a benefit in the brainstorming.

The meeting was started with a brief summary of the master thesis and the problem description and decomposition. Objectives and scope were presented together with the design challenges in today's designs. Current designs and invention requests were displayed to give the participants a basic understanding of the potential design solutions that can be implemented. The group also discussed the load case and API 662, to get an understanding of what kind of loads that the feet are exposed to.

After the introduction, all team members had 15 minutes to individually create concepts of a solution to the design challenges. It was encouraged to produce as many concepts as possible and no ideas were discarded. After the individual concept generation, each member had the chance to present their concepts for the entire team and a discussion of the concepts was initiated. Once all members had presented their concepts, a more general discussion followed. The presented concepts were tweaked and similarities between concepts were analysed. Different concepts were tried to be combined if possible.

## 5.5 Generated Concepts

Concepts generated in the brainstorming during the concept generation session and during the external searches were summarised and analysed. Some concepts were considered unfit for the case and were therefore ruled out. In the end of the concept generation, eleven concepts had been generated. These concepts were transferred into the concept scoring.

Unfortunately, due to confidentiality and potential patent applications, the concepts can not be disclosed.

# 6 Concept Scoring and Selection

## 6.1 Selection Criteria

The concept scoring was based on seven fields identified as important to the success of a foot design. Each field then consisted of one or more criteria related to that field which would further nuance the scoring as seen in Figure 22. Even though the aim of the scoring was to find independent criteria, some criteria became coupled. For example, a complex manufacturing process, and tight tolerances usually leads to a high cost.

| Concept Scoring | | | | |
|---|---|---|---|---|
| **Criterion Field** | **Criterion No.** | **Selection Criterion** | **Weight** | **Weight per field** |
| Supply Chain | 1 | Globality of components and material | 7,5% | 7,5% |
| Manufacturing | 2 | Complexity and number of parts | 10,0% | 25,0% |
| | 3 | Tolerances | 10,0% | |
| | 4 | Manufacturing steps and techniques used | 5,0% | |
| Assembly | 5 | Ease of assembly | 5,0% | 10,0% |
| | 6 | Assembly unambiguity | 5,0% | |
| Service | 7 | Ease of service | 7,5% | 17,5% |
| | 8 | Number of tools needed | 5,0% | |
| | 9 | Tool complexity | 5,0% | |
| Modularity | 10 | Adaptivenes to other sizes of GPHE | 10,0% | 10,0% |
| Design Impact | 11 | Impact on other frame components | 10,0% | 10,0% |
| Cost | 12 | Overall cost estimation | 20,0% | 20,0% |
| | | **Total score** | 100,0% | 100,0% |

**Figure 22: Criteria and weighting of criteria used in the concept scoring.**

The criterion concerning supply chain was derived from the interview with the second senior development engineer who mentioned the issues with unifying designs manufactured using components based on different standards. Criterion number 1 was therefore rating the concepts based on the global availability of components used in the concepts. High availability gave a high score. The weight of the field was however considered relatively low.

Manufacturing was considered the most important field in the scoring and was in total weighted 25% of the score. This was due to the large impact manufacturing has on cost and the finished product overall. Following the facts stated in the theory, the complexity and number of parts are of highest importance and therefore stood for a large part in manufacturing. As mentioned above, some criteria became coupled, and the complexity was one example of this. Complexity in a part influence many more aspects of the design than manufacturing and manufacturing costs. Because of this, part complexity could have been sorted in other fields but were considered to affect manufacturing the most. Apart from the complexity in a part, it was considered that the required tolerances affected the manufacturing the most, and also the different manufacturing steps or techniques used.

The third identified field was assembly. This field was included to score the concepts on how easy and intuitive the concepts could be assembled. This is also a major part in reducing the costs as an easier and more intuitive assembly process cuts time and faults which in turn cuts costs. The assembly process was considered to have a relatively small impact on the concepts as a whole. This was due to the life span of GPHEs tend to be long and thereby making other types of service processes more important.

Service was considered to be one of the most important factors in the scoring of the concepts. It was underlined in the project description and the conducted interviews with service focused employees. Service was broken down into three criteria. Ease of service aimed to score the complexity and number of steps taken to perform a service of the feet and GPHE as a whole. More steps and complexity in process gave a lower score. Number of tools tried to focus on how much equipment was deemed required to perform the service operation. Tool complexity instead focused on scoring how advanced equipment that would be needed. These criteria were based on the conversation with the product expert and the site service manager.

Modularity was identified as an important field if the concepts would be implemented widely in the product range of GPHEs. A large number of different articles and feet are costly from and administrative viewpoint and therefore it was favourable if the concepts easily could be adapted to other sizes of GPHE.

Some concepts required an alteration of already existing articles such as frame- and pressure plate. These alterations would have created a process to change these parts and perhaps even re-certify them according to standards. Certification, for example according to applied pressure vessel norms, can be very time consuming and costly. To score the concepts on this, the “Design Impact” field was chosen. It scores the concepts on how much work on other components would be required to implement the concept.

Lastly, a criterion for the overall costs was included. This would score the concept on the estimated overall cost, and thereby also include costs that could have been overlooked in earlier criteria. Cost was also the criterion deemed most important based on the conducted interviews.

## 6.2 Scoring Process and Results

To get a more nuanced scoring and reflections from more experienced engineers, the scoring was conducted together with three development engineers. They provided the expertise and knowledge the project taker lacked in the internal manufacturing processes and in engineering as a whole.

The scoring was conducted through evaluating each concept on one criterion at the time and then progressing to the next criterion. Thereby focus remained on the criterion to get a fair scoring throughout the concepts. The result from the scoring done by the group of the project taker and the experienced engineers can be seen in Figure 23 below.

## Concept Scoring

| Criterion Field | Criterion No. | Selection Criterion | Weight | Weight per field | Concept 1 | Concept 2 | Concept 3 | Concept 4 | Concept 5 | Concept 6 |
|---|---|---|---|---|---|---|---|---|---|---|
| Supply Chain | 1 | Globality of components and material | 7,5% | 7,5% | 3 | 4 | 5 | 4 | 4 | 5 |
| Manufacturing | 2 | Complexity and number of parts | 10,0% | 25,0% | 5 | 4 | 5 | 5 | 5 | 4 |
| | 3 | Tolerances | 10,0% | | 2 | 3 | 5 | 5 | 5 | 1 |
| | 4 | Manufacturing steps and techniques use | 5,0% | | 3 | 4 | 4 | 4 | 5 | 3 |
| Assembly | 5 | Ease of assembly | 5,0% | 10,0% | 4 | 3 | 4 | 3 | 5 | 5 |
| | 6 | Assembly unambiguity | 5,0% | | 3 | 4 | 4 | 3 | 5 | 5 |
| Service | 7 | Ease of service | 7,5% | 17,5% | 1 | 2 | 3 | 3 | 1 | 4 |
| | 8 | Number of tools needed | 5,0% | | 1 | 2 | 3 | 3 | 1 | 4 |
| | 9 | Tool complexity | 5,0% | | 1 | 2 | 3 | 3 | 1 | 4 |
| Modularity | 10 | Adaptivenes to other sizes of GPHE | 10,0% | 10,0% | 3 | 3 | 4 | 4 | 5 | 1 |
| Design Impact | 11 | Impact on other frame components | 10,0% | 10,0% | 1 | 2 | 5 | 5 | 1 | 4 |
| Cost | 12 | Overall cost estimation | 20,0% | 20,0% | 3 | 2 | 3 | 4 | 4 | 2 |
| | | **Total score** | 100,0% | 100,0% | 30 | 35 | 48 | 46 | 42 | 42 |
| | | **Weighted score** | | | 2,6 | 2,8 | 4 | 4,025 | 3,625 | 3,125 |

| | |
|---|---|
| Min Score | 1 |
| Max Score | 5 |
| Min Total Score | 12 |
| Max Total Score | 60 |

## Concept Scoring

| Criterion Field | Criterion No. | Selection Criterion | Weight | Weight per field | Concept 7 | Concept 8 | Concept 9 | Concept 10 | Concept 11 |
|---|---|---|---|---|---|---|---|---|---|
| Supply Chain | 1 | Globality of components and material | 7,5% | 7,5% | 5 | 4 | 5 | 5 | 5 |
| Manufacturing | 2 | Complexity and number of parts | 10,0% | 25,0% | 5 | 5 | 5 | 5 | 4 |
| | 3 | Tolerances | 10,0% | | 5 | 4 | 5 | 3 | 3 |
| | 4 | Manufacturing steps and techniques use | 5,0% | | 3 | 3 | 5 | 4 | 3 |
| Assembly | 5 | Ease of assembly | 5,0% | 10,0% | 5 | 4 | 5 | 4 | 3 |
| | 6 | Assembly unambiguity | 5,0% | | 4 | 4 | 5 | 4 | 3 |
| Service | 7 | Ease of service | 7,5% | 17,5% | 1 | 4 | 1 | 4 | 1 |
| | 8 | Number of tools needed | 5,0% | | 4 | 4 | 5 | 4 | 1 |
| | 9 | Tool complexity | 5,0% | | 4 | 4 | 5 | 4 | 1 |
| Modularity | 10 | Adaptivenes to other sizes of GPHE | 10,0% | 10,0% | 4 | 4 | 5 | 4 | 4 |
| Design Impact | 11 | Impact on other frame components | 10,0% | 10,0% | 4 | 5 | 1 | 3 | 1 |
| Cost | 12 | Overall cost estimation | 20,0% | 20,0% | 3 | 3 | 5 | 2 | 1 |
| | | **Total score** | 100,0% | 100,0% | 47 | 48 | 52 | 46 | 30 |
| | | **Weighted score** | | | 3,85 | 3,95 | 4,3 | 3,825 | 2,4 |

| | |
|---|---|
| Min Score | 1 |
| Max Score | 5 |
| Min Total Score | 12 |
| Max Total Score | 60 |

**Figure 23: The concluding scores of all concepts.**

## 6.3 Scoring Reflection

As seen in the scoring above, the most promising concepts were Concept 9, Concept 4 and Concept 3 in descending order. These three concepts were further investigated to assure their relevance and feasibility.

The highest scoring concept was Concept 9, that gained a lot in the scoring from its simplicity. However, it also scored poorly in some categories such as ease of service and impact on other frame components. These scores were low because the concept more or less was unable to be serviced and had a great influence on the frame and pressure plate. Large modifications to the PP could result in demands to verify the PP in terms of structural integrity and pressure vessel certification. A time-consuming and costly consequence. Concept 9 was also found to have another vital flaw regarding the ability to acquire load in the X-direction. It was therefore concluded during the reflection of the scoring that Concept 9 should be disqualified for its vital flaws. Concept 9 scores the best but had major “hidden” flaws that will discard the concept in further development and verifications

The other two concept that received the highest scores were kept for further in-depth development.

# 7 In-Depth Development & Design Review

*The progressing concepts, Concept 4 and Concept 3 now got the status of being design suggestions in the in-depth development. Concept 4 was henceforth called "Design 1" and Concept 3 was called "Design 2".*

## 7.1 Design 1

Design 1 consisted of standardised L-profiles joined by the bolts and potential welding. As the purchase study shows that the majority of feet are produced in China, it was deemed appropriate to adapt the design to the Chinese manufacturing standards. The Chinese standard including L-profiles is denoted GB/T 706-2008 and was used in the in-depth development.

The first focus became to find a profile that would fulfil the ground clearance requested. No profile in the mentioned standard had the required dimensions to make the ground clearance optimal. The closest to the optimal dimension would interfere with the flange of the mounted connections. The height was too tall without any modifications. No other profile was able to fulfil the desired dimensions set by the target specification. A design using L-profiles that did not need processing was therefore scrapped.

An attempt to modify the design without removing the essence of the design was made. Because the modified design had two components it was also assumed necessary to weld the two parts together.

## 7.2 Design 2

The in-depth development of Design 2 was not as extensive as Design 1. Design 2 kept many traits from existing reinforced feet. Design 2 did not need to comply with any geometrical standards as the idea was to machine the entire foot.

## 7.3 Design Review

In the finishing stages of the in-depth development a design review was held to all frame design engineers at the R&D department. The project and its process were presented to the engineers to make sure everyone understood the scope of the project. The two designs that went through the in-depth development and the reasoning behind were presented. The engineers could then ask questions and give feedback on the process and decisions. Some of the feedback given during the design review is presented in the list below.

- Could it be beneficial to loop the in-depth developed designs into the scoring again to get a more even evaluation?
- Would it be better or easier to use a fixed reference in the scoring?
- Have you investigated the tolerances of the underside of the frame- and pressure plate?
- If the designs prove beneficial, could you instead of creating a completely new design, simply place shims under the frame- and pressure plate?

**Feedback reflection**

The above bullets were contemplated and investigated after the design review. Design 1 differed much from the original concept and could be scored again to evaluate it properly. This was not done for two reasons. Firstly, the scoring was done in a group with three development engineers with a busy schedule. Time was not enough to book a meeting as such without delaying the project. Secondly, it is not certain that the group would make the same decisions at that session as a long time had progressed since the original scoring. However, Design 1 was deemed to have become worse after the in-depth development. Design 1 does not use the intended L-profiles and requires more processing in terms of welding and cutting. Therefore, it was downgraded and not chosen as a final design.

A reference in the scoring could have helped in maintaining a consistent scoring level. The reason behind how the scoring was done is that the methodology proposed using a relative scoring.

It was discovered that the tolerance for squareness on the underside of frame- and pressure plate was between 3 and 3,5 mm. This means in theory that one foot could have a 3,5 mm gap between foot and plate. This issue has not been acted upon but noted.

Shims are a cheap alternative to the suggested design. It can be implemented on already existing design without any major changes. The shims would however not be attached to any component and therefore risk moving around as the GPHE is exposed to altering loads.

# 8 Design Verification and Calculations

To verify the selected design, a finite element model was set up with the established external loads acting on the feet. The program used was ANSYS Workbench and the model was developed together with a mechanical analyst at the department of mechanical technology. The aim of the simulation was to evaluate the bolted connection rather than the structural integrity of the foot. Since the FE-model was developed in this project and thus had not been used before, a reference needed to be established. This was done by using the same FE-model with the already existing reinforced swing foot, and furthermore comparing to existing verification tools. Only the foot adapted to the T45 GPHE was used throughout the verification process due to time constraints. Furthermore, only the foot positioned at the frame plate was analysed. Feet positioned at the frame plate are exposed to higher loads than the feet positioned at the pressure plate. This can be seen in the section “Load Cases” below. An overview of the model and coordinate system used is seen in Figure 24. Note that the positive direction for Z is directed downwards unlike previously in the project.

In order to avoid large contact surfaces and complex models that could be difficult and time consuming to converge, the bolts were exchanged for joints and springs. Initially bolts were attempted but due to converging issues a new model was developed. In the new model, each bolt was exchanged for a spring with the appropriate stiffness and the interfaces between foot and plate had a joint.

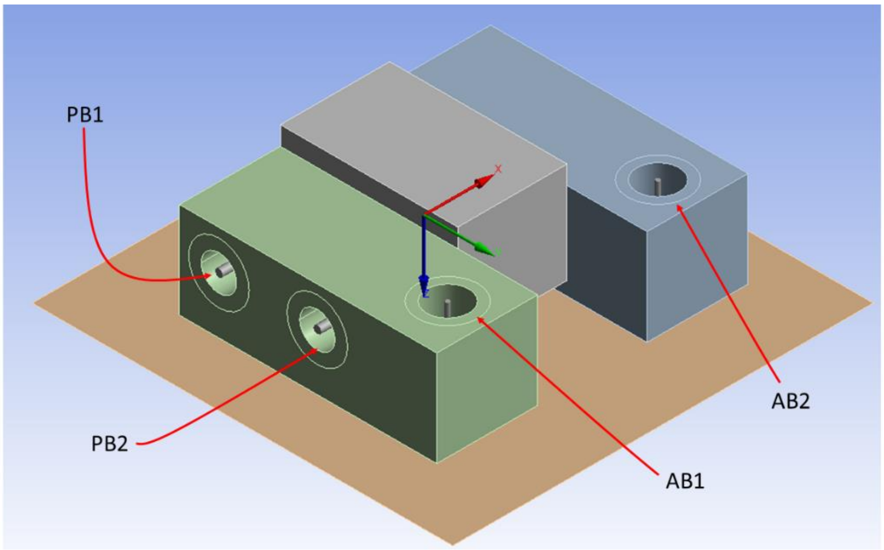


**Figure 24: Overview of the FE-model.**

# 8.1 Set up

## 8.1.1 **Load Cases**

The external loads described in the background section are general and meant to be applied to the port holes of the GPHE. In order to translate the loads from the port to loads acting on the feet, an internally developed program was used. The translation program translates the external loads from the port to a point positioned close to the foot in the frame- or pressure plate. The program calculates and takes into consideration the configuration of the GPHE, for example number of channel plates, weight of channel plates, and overall dimensions.

For this case a specific product, a T45, with the characteristics to be a worst-case scenario in terms of weight and loads was used to establish the numerical values of the model. In Table 11 the maximum positive loads are presented, and in Table 12 the maximum negative loads are presented. The position in the table describes the left or right pair of feet on the frame- or pressure plate.

**Table 11: Maximum positive loads acting in the load centre provided by the internal translation programme.**

| ***Position*** | ***X*** | ***Y*** | ***Z*** |
|---|---|---|---|
| FP1 | 192 829 N | 71 429 N | 375 160 N |
| FP2 | 192 829 N | 71 429 N | 375 160 N |
| PP1 | 0 | 33 321 N | 234 363 N |
| PP2 | 0 | 33 321 N | 234 363 N |

**Table 12: Maximum negative loads acting in the load centre provided by the internal translation programme.**

| ***Position*** | ***X*** | ***Y*** | ***Z*** |
|---|---|---|---|
| FP1 | -192 829 N | -71 429 N | -153 475 N |
| FP2 | -192 829 N | -71 429 N | -153 475 N |
| PP1 | 0 | -33 321 N | -12 224 N |
| PP2 | 0 | -33 321 N | -12 224 N |

The loads can act in combinations and therefore four different load cases were defined. Each load case has a unique combination of the maximum positive and maximum negative load in the Y- and Z-direction. Because the model is symmetrical in the YZ-plane it was decided to not distinguish between positive and negative loads in the X-direction. It was assumed that the result would be equal but swapped between the anchor bolts when changing the X-direction. In Table 13 the identified load cases are presented. Note that the X-direction was kept positive throughout all load cases to minimise the number of cases.

**Table 13: The identified load cases.**

| | ***X*** | ***Y*** | ***Z*** |
|---|---|---|---|
| Load case 1 | + | + | + |
| Load case 2 | + | - | + |
| Load case 3 | + | + | - |
| Load case 4 | + | - | - |

### 8.1.2 **Contacts**

Contacts between foot and plate were kept same for all contacting surfaces. They were altered between a frictionless interaction to frictional with a friction coefficient of either 0,2, 0,3 or 0,4 as described in the theory. The alternation was done to establish the influence of the friction in the model. Once it had been established, the testing of the new design was done with a single frictional contact.

### 8.1.3 **Joints**

Joints were positioned at the locations where bolts would have penetrated the contact surface between foot and plate, as see in Figure 25. The purpose of the joints was to transfer the loads from plate to foot and thus also detect the shear forces acting on the bolt. All joints were applied to the holes for the bolt and free to rotate around the axis through the length of the perceived bolt.

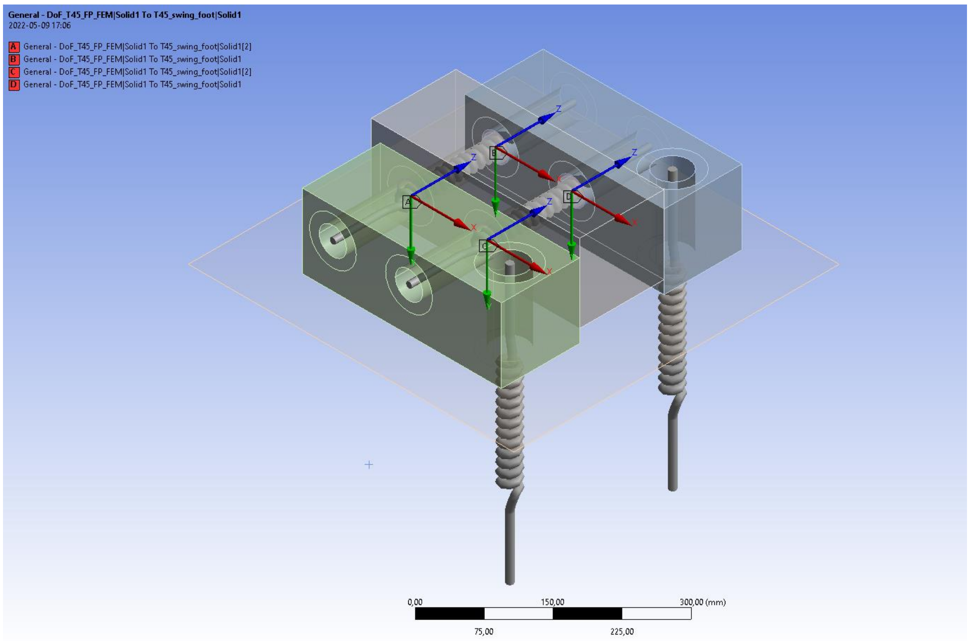


**Figure 25: Joints in the FE-model.**

### 8.1.4 **Springs**

Springs were used to simulate the tensional loads in a bolted connection. The springs were applied at the positions of the plate and anchor bolts, as seen in Figure 26. A modelled surface with the geometry of an appropriate washer was used as the source on the feet. Anchor bolts were modelled as body-to-ground with the length of a recommend anchor bolt. Stiffnesses for the springs were calculated according to equation (8.1), derived from combining equations (2.3), (2.4), (2.5) and (2.6).

$$S = \frac{EA}{L} \tag{8.1}$$

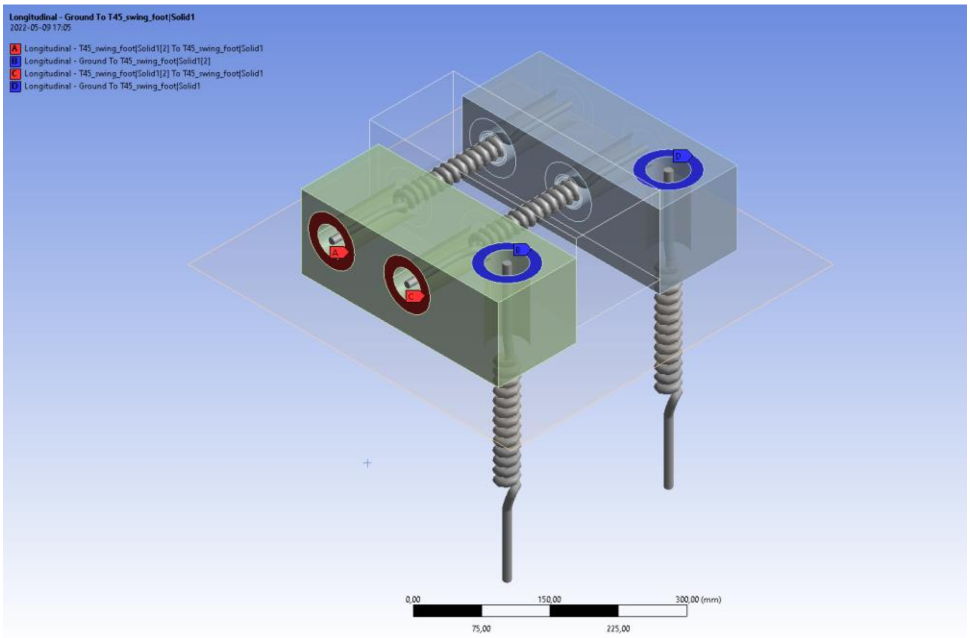


**Figure 26: Springs used in the FE-model.**

### 8.1.5 **Mesh**

All mesh were program controlled in terms of method. This resulted in a Hex-dominant mesh for the plate dummy and foundation. The feet had a tetrahedral mesh to manage the bolt holes directed in different directions. Several sizes of mesh were tested on the feet to determine a fair result. It was found that the results converged when the mesh became about 10 mm. To get a smoother mesh around the bolt holes and the washer area, a sizing of 5 mm was added to these areas. The complete mesh is seen in Figure 27.

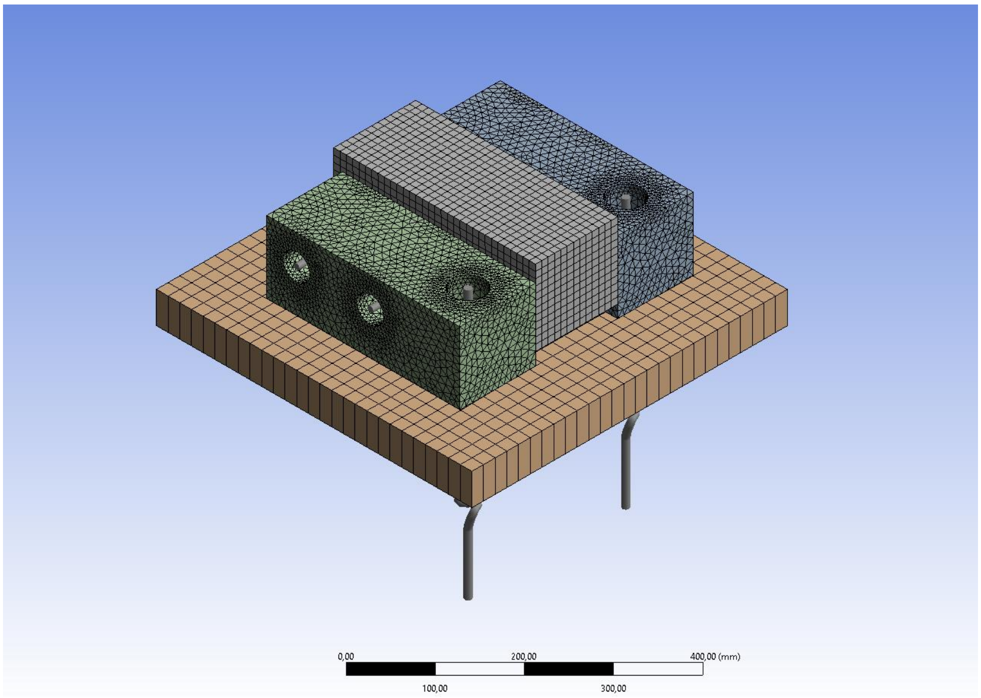


**Figure 27: The mesh used in the FE-model.**

### 8.1.6 **Loads and Constraints**

The external loads were applied with a remote force to a point resembling the point calculated with the internal translation programme. The foundation was set as fixed support to become stationary. The feet were constrained by a displacement acting on the bottom washer area. The displacement was set to 0 mm in the Y-direction for AB1 and 0 mm in both Y- and X-direction in AB2. This was to eliminate potential risks of over constraining the model and thus creating non-realistic reactional forces. This also ensure to create a worst-case scenario on AB2.

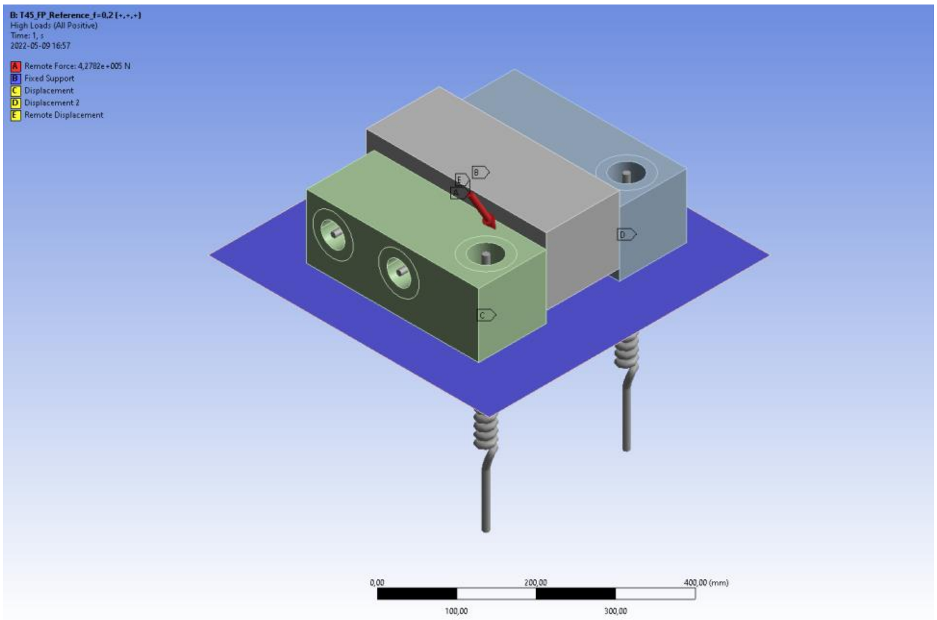


**Figure 28: Applied load and constraints in the FE-model.**

## 8.2 Results

Stresses in the bolts were calculated by first extracting the tensile- and shear forces from the FE-model and divide the force with the respective bolt area. Shear forces in the plate bolts were averaged in the Y-direction to counter the potential loads originating from constraining the model too tightly.

Allowable tension and shear stress was calculated according to ASME III div1 NF level B as follows:

$$\sigma_a = min(\sigma_y; 1{,}15 \cdot 0{,}5 \cdot \sigma_u) \tag{8.2}$$

$$\tau_a = min(0{,}6 \cdot \sigma_y; 1{,}15 \cdot \frac{0{,}62}{3} \cdot \sigma_u) \tag{8.3}$$

Usage was calculated by combining tensile and shear stress according to NF-3324.6 as it covers the individual criteria as well, see equation below. Usage describes the ratio between the occurring stresses and the allowable stresses.

$$U = \sqrt{\left(\frac{\sigma}{\sigma_a}\right)^2 + \left(\frac{\tau}{\tau_a}\right)^2} \tag{8.4}$$

### 8.2.1 **Frictional Impact**

The first part in the evaluation of the foot was to set a baseline. In this process, it became interesting to compare different frictional coefficients (f) and its impact on the bolts. The test was set up with four different coefficients ranging from frictionless (f=0) to f=0,4, all done with the existing reinforced swing foot. The results can be seen in Figure 29 to Figure 32.

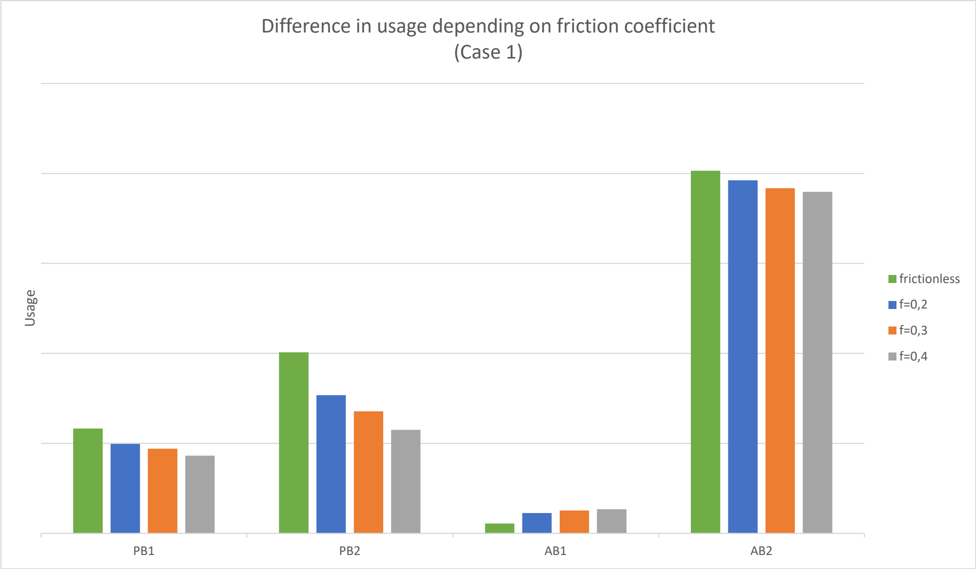


**Figure 29: Chart presenting the bolt usage in load case 1 with different frictional coefficients.**

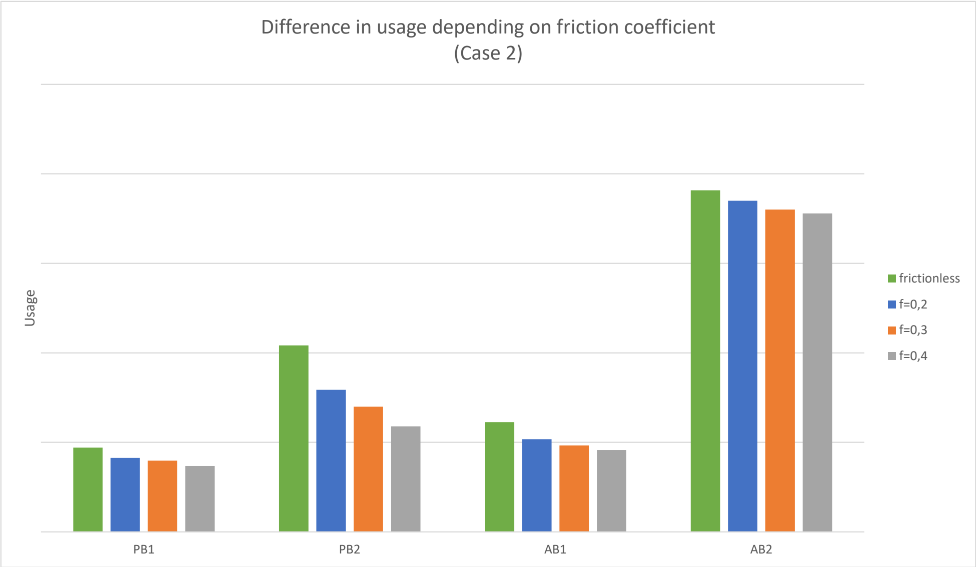


**Figure 30: Chart presenting the bolt usage in load case 2 with different frictional coefficients.**

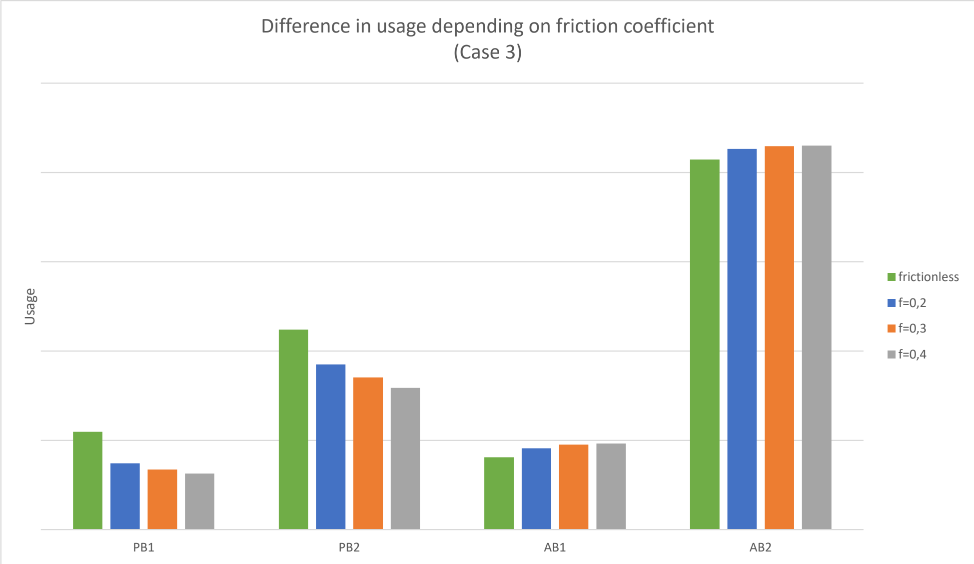


**Figure 31: Chart presenting the bolt usage in load case 3 with different frictional coefficients.**

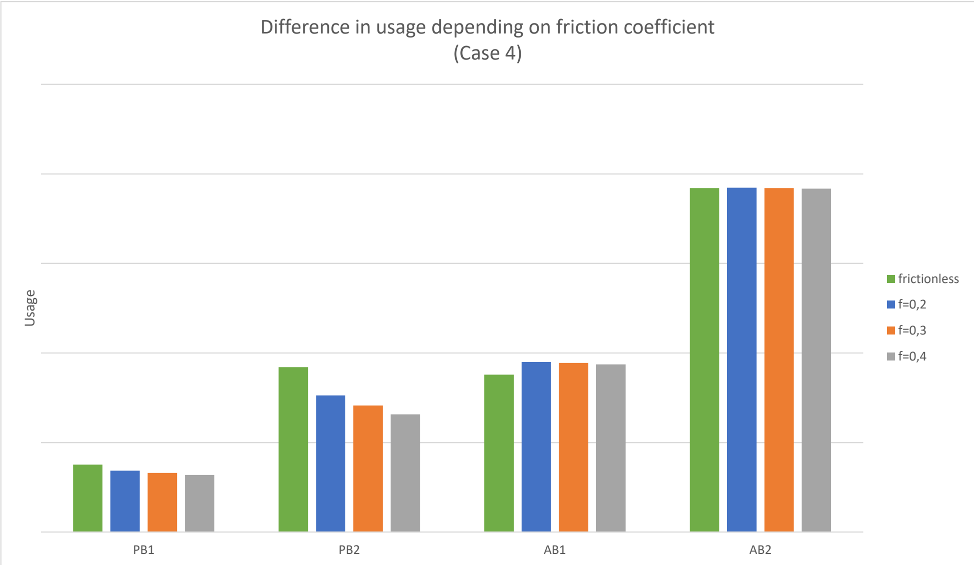


**Figure 32: Chart presenting the bolt usage in load case 4 with different frictional coefficients.**

As seen in the above charts, the frictional coefficient has an impact on the usage of the bolts. The impact is larger in load case 1 and 2, and smaller in load case 3 and 4. Tests with a larger frictional coefficient generally decrease usage of the bolts.

It can also be distinguished from the charts that the bolt with the highest usage is AB2. In many cases it has a usage more than twice as large as the plate bolts. This would indicate that the anchor bolts in general, and the anchor bolt in the direction of the applied X-force specifically, is the most exposed component.

### 8.2.2 **Preload Impact**

To test another factor in the bolted joint, a study of the impact of preloaded bolts was conducted. A frictional coefficient of 0,4 was used to determine if a preloaded plate- and anchor bolt would change the results significantly. Three levels of preload were studied, no preload, a low preload, and a high preload. The preloads were calculated using the guideline from Colly Components. The function was simplified to better accommodate the swift procedure in the study. Equation (8.5) and (8.6) below shows the used formulas where (8.5) gives the preload force of the high preload and (8.6) gives the preload for the low preload.

$$F = 0{,}7 \cdot R_{eL} \cdot A_t \tag{8.5}$$

$$F = 0{,}5 \cdot R_{eL} \cdot A_t \tag{8.6}$$

In Figure 33 to Figure 36 the results of the study are presented for all described load cases compared with the unloaded reference. The charts show that in all bolts except AB2, the preload increases the usage of the bolts. In AB2 the preloaded cases show a lower usage but the difference between the high and low preload are small.

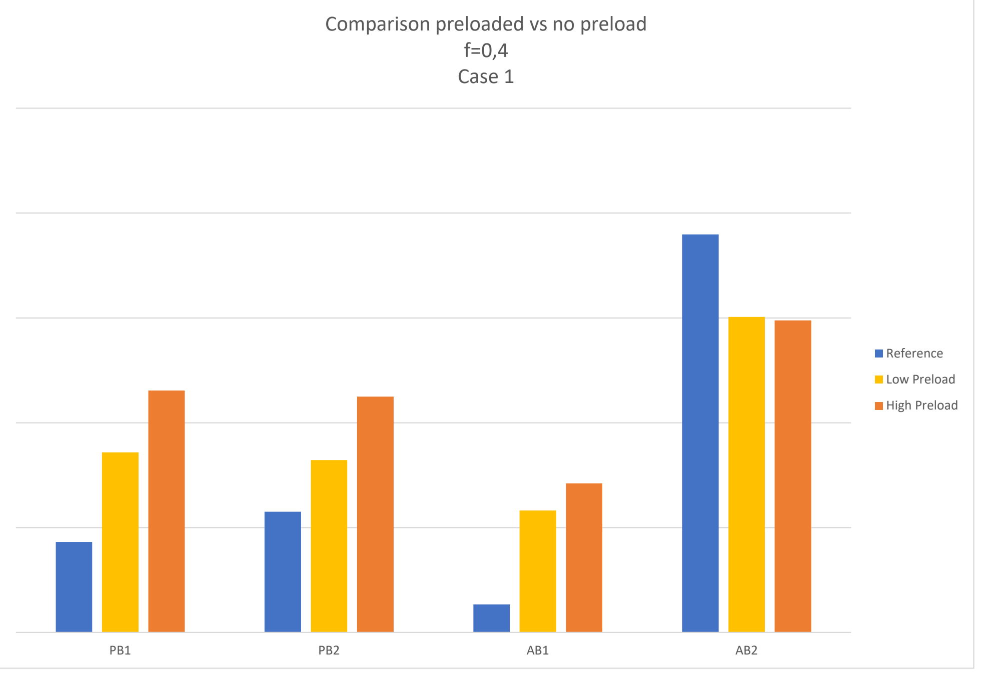


**Figure 33: Chart presenting the bolt usage in load case 1 with different preloads.**


**Figure 34: Chart presenting the bolt usage in load case 2 with different preloads.**

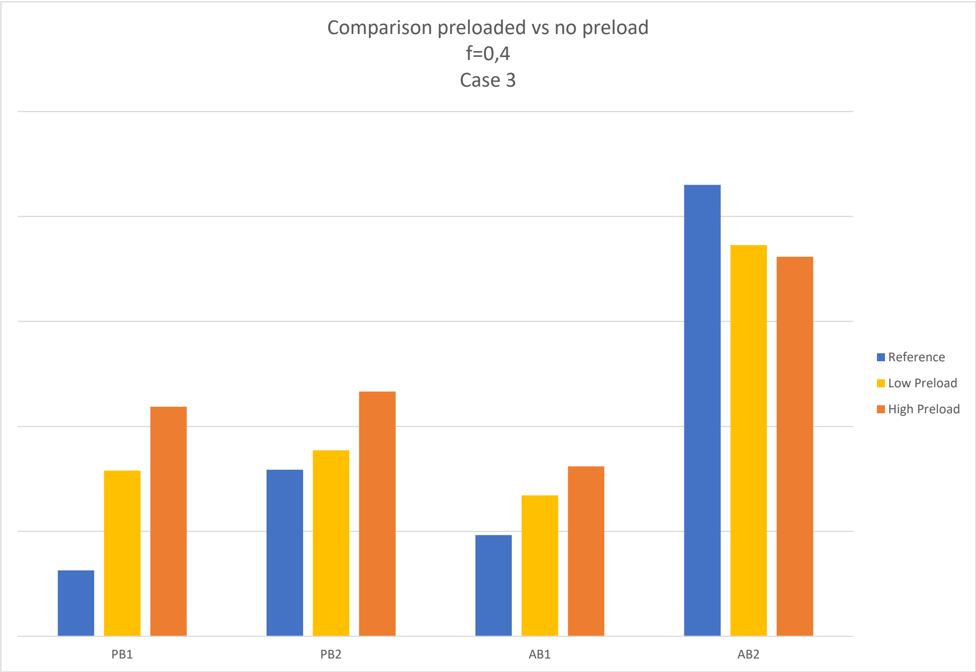


**Figure 35: Chart presenting the bolt usage in load case 3 with different preloads.**

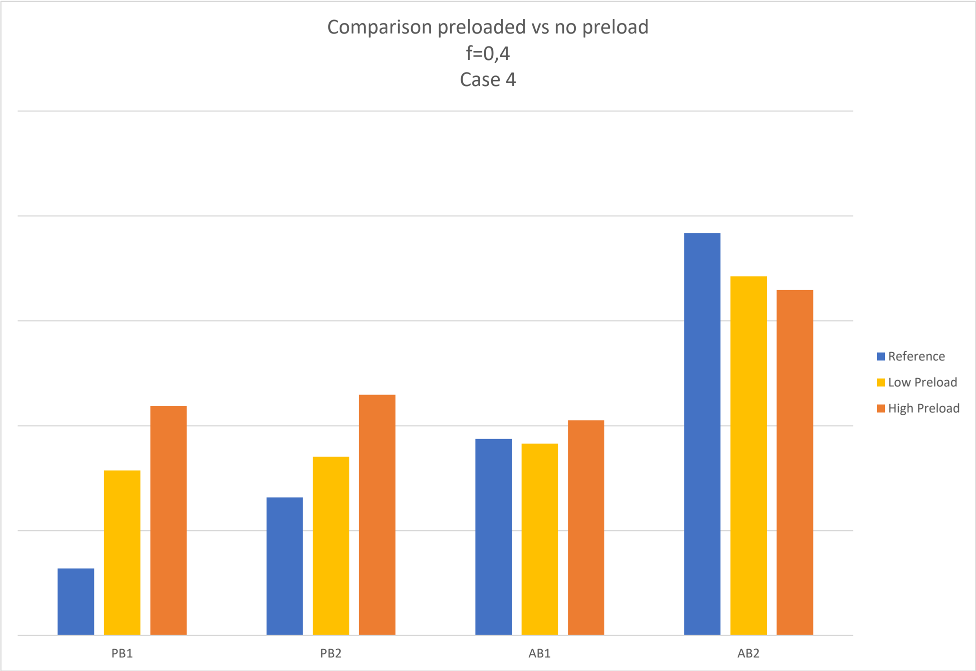


**Figure 36: Chart presenting the bolt usage in load case 4 with different preloads.**

The results from the test of the preloaded impact above showed that a higher preload increases the usage in all bolts but AB2, in almost all load cases. In load case 4, AB1 did not show an increased usage from no preload to the low preload. The underlaying data showed that the overall increased usage depends on the added tensional stresses induced by the preload. AB2 benefits from the added preload, but an increased preload from low to high does not reduce the usage much more. In Table 14 the difference in adding a high preload to a no preload bolt is presented. Some bolts experienced an increase of several hundred percent. The large differences were due to minor decreases in shear stresses while the tensional stresses increased a lot.

**Table 14: Difference in usage between no preload and high preload as a ratio of the non-preloaded bolts.**

| | ***PB1*** | ***PB2*** | ***AB1*** | ***AB2*** |
|---|---|---|---|---|
| Load case 1 | 167 % | 95 % | 446 % | -22 % |
| Load case 2 | 208 % | 90 % | 104 % | -22 % |
| Load case 3 | 252 % | 48 % | 69 % | -16 % |
| Load case 4 | 241 % | 74 % | 10% | -14 % |

### 8.2.3 New Design Comparison

In the comparison between the new design (Design 2) and the already existing reinforced swing foot, no preload was added. A frictional coefficient of 0,4 was used as it was considered the most adequate for the surfaces according to the theory. Figure 37 to Figure 40 present the results from the comparison in the different load cases.

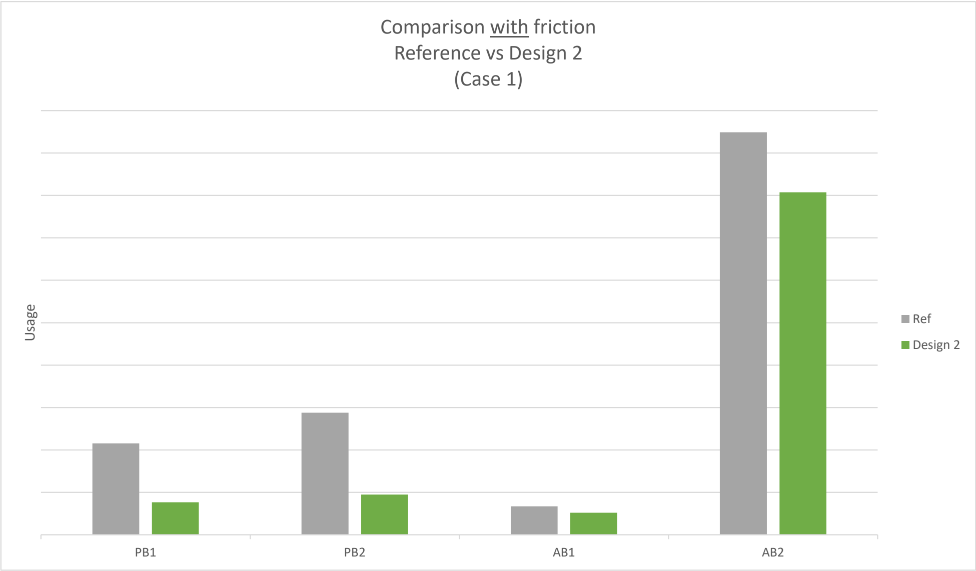


**Figure 37: Chart presenting the comparison between the new suggested design and the existing design as reference in load case 1.**

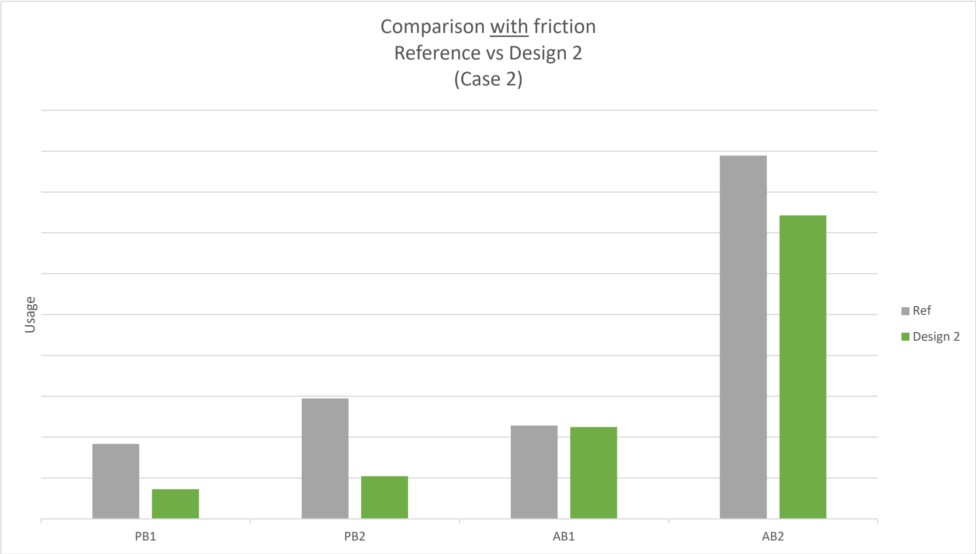


**Figure 38: Chart presenting the comparison between the new suggested design and the existing design as reference in load case 2.**

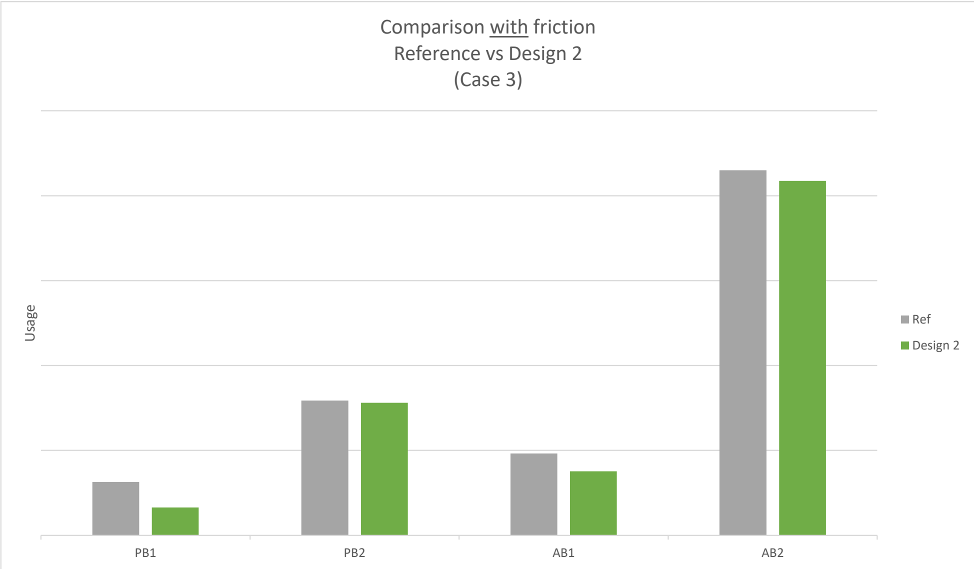


**Figure 39: Chart presenting the comparison between the new suggested design and the existing design as reference in load case 3.**

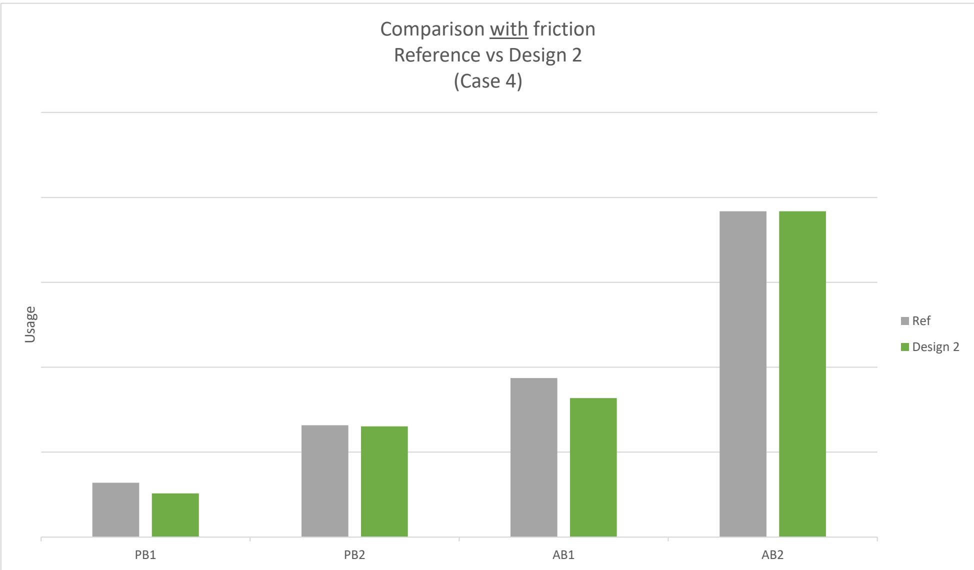


**Figure 40: Chart presenting the comparison between the new suggested design and the existing design as reference in load case 4.**

The usage difference in the bolts in load case 1 and 2 are more significant than in load case 3 and 4. Generally, plate bolts tend to be more affected than anchor bolts. In all cases the bolt usage is lower or the same in the new suggested design. In Table 15 below the results for the new design is summarised. The table shows the difference in usage the suggested design yields.

**Table 15: Summary of the difference in bolt usage between existing solution and suggested design.**

| | ***PB1*** | ***PB2*** | ***AB1*** | ***AB2*** |
|---|---|---|---|---|
| Load case 1 | -65 % | -67 % | -23 % | -15 % |
| Load case 2 | -59 % | -64 % | -2 % | -16 % |
| Load case 3 | -48 % | -1 % | -21 % | -3 % |
| Load case 4 | -19 % | -2 % | -13 % | 0 % |

# 9 Discussion

## 9.1 The Development Process

In the beginning of the project, the methodology of U&E described the process of identifying customer needs. Because Alfa Laval produces products aimed towards other business and thus focuses on business to business (B2B) relations, the customer becomes a whole company. This imposes problems, especially for an external project like this, as one needs to find the right competence in another company. To solve this, the identifying customer needs was interpreted as to identify the needs of the end user or person with the closest contact with the product. In this project that became service personnel, product experts and product managers. These were the people that were considered closest to the customer and the people with the most extensive product contact. The risk of using the perspective of in-house employees is that it can be biased and not identifying the issues entirely. Therefore, using U&Es method for identifying customer needs and establishing product specification is not considered optimal in B2B products as it is tough to come by unbiased data from customers. From the experience made through this project it was considered that U&E's method could be better suited for business to consumer (B2C) products or potentially in an earlier stage by the market researchers.

The process of generating concepts described by U&E turned out useful. To search for inspiration both internally in the company and externally through patents and general constructions was helpful in broadening the perspective in concept generation. The systematic approach made sure that the concept generation did not get stuck in one or a few ideas. From the project perspective it is believed that an even more systematic and nuanced concept generation process could be helpful. For example, the brainstorming could be conducted in a more systematic way to ensure that more perspectives are discussed.

Scoring the concepts in this project was also based on the U&E process of relative scoring. As mentioned during the design review this could seem less structured compared to using a reference. This is valid critique, and a reference could very well be implemented to make the scoring more concrete. The issue in this case was to find a good reference. Another thing to highlight during the concept scoring was the number of concepts scored. Scoring eleven concepts takes a lot of time and should be avoided. Instead, it is proposed to do a screening in an earlier stage where the feasibility and other important characteristics are judged.

Overall, the methodology and process used during this thesis have been beneficial. Implementing traits from the development process used by Alfa Laval, such as the design review, had a great result. It presented some issues and questions that had not yet been discovered.

The results presented a different scenario than what was expected. It was expected that the plate bolts would be the most exposed bolt and therefore the entire development process was aimed at minimising the usage of the plate bolts. In hindsight, a first test of the load case should have been conducted to identify the weak bolts with certainty.

## 9.2 Design Result

The new suggested design, Design 2, does not differ much from already existing foot designs. This is seen as beneficial as it makes a potential implementation easier. Manufacturers already have knowledge in how to best produce said foot and can hopefully easily change their manufacturing processes to achieve the slight differences in the design. Transportation of assembled GPHEs and packaging does not need any changes as the bolt positions are identical and therefore can use the same mounting in the packaging. The height and ground clearance are kept identical to facilitate exchanging old GPHEs to new ones with the new feet. The kept height also ensures a good fit to existing pipe connections.

Potential issues could appear as a result of the new design changes. Corrosion could be more prominent and potentially gather underneath the frame- or pressure plate. To prevent this, the new design has been designed to avoid water collection by reducing the size of the exposed parts. As the new foot is intended to use the same materials as existing designs, already used surface treatments should also be applicable to prevent corrosions.

Cost for the new design is hard to estimate. The new design and its intended manufacturing process could result in a slightly larger piece of raw material compared to current reinforced swing design. Due to increasing raw material prices in 2022 the increased raw material use could have a large impact on the price of the new design.

## 9.3 Verification Results

It could be seen in the test regarding the frictional impact that an increased friction in the model decreased the bolts usage. The usage also seemed to decrease in a somewhat linear manner. This would indicate that the applied force onto the foot gets transferred by frictional forces rather than through the bolts. The same impact could not be seen in the anchor bolts through load case 3 and 4 as the force in the Z-direction is directed upwards. This is probably due to smaller contact pressures between the underside of the foot and the foundation as frictional force is proportional to the normal contact force. Even though a difference in usage could be distinguished between the different frictional cases, the difference was not that significant. Increases of 50% in friction did not yield more than about 15% decrease of usage. The relatively small difference in usage could be explained with the lack of preloaded forces. As the model did not use preloads, it was not ensured that a full contact between the joint surfaces were maintained. The set-up of the model could also be a reason for certain faults in the results. The joints used were constrained to identify shear loads in the joint surfaces without any gap between bolt and bolt hole. Because the joints were tightly constrained, there is a risk that the joint detects shear forces despite the frictional forces. To ensure this does not happen, a small gap in the joint could be included.

The preloaded tests showed that almost all bolts get an increased usage when a preload is applied. This is an indication that the shear loads do not decrease in the extent where a preload would be deemed beneficial. The only decrease in usage from applying a preload is seen in AB2. AB2 is the bolt which has the highest usage throughout the test and a decrease in usage in AB2 would be sought after. However, the minimal decrease in AB2 does not compensate for the much higher usage in the rest of the bolts. Again, these tests, could be affected by the tightly constrained joints. A test with the same conditions but a small gap in the joint should by conducted to verify the results.

Throughout the test of the existing design and the new design it was clearly seen that the most exposed bolt was AB2. Partly this was because AB2 was deliberately constrained to take up all loads in the X-direction, to prevent over constraining the FEM-model. Brief test where both AB were constrained in X- and Y-direction were conducted, and the results were similar. Thus, the conclusion was that AB2 has a slightly elevated usage from what could be considered “reality” but will still be the most exposed bolt in the foot.

The new design did decrease the usage in the plate bolts significantly, especially in load case 1 and 2 where the load in the Z-direction was directed downwards. Plate bolts in load case 1 and 2 had a decreasing usage of between 59 – 67 %. Anchor bolts experienced a decrease in usage as well but not as significantly. The new design improves or leave the usage unchanged in all bolts and in all cases.

## 9.4 Future Work

To better validate the results presented in this report another updated simulation would be beneficial to conduct. In this simulation, the friction, preload, and overall stresses should be evaluated. The model should use looser constraints for the joints in the FEM-model to ensure that the stresses originate from the applied loads. Furthermore, the results could be further validated if it could be compared to calculations according to Eurocode 3. Therefore, it is suggested that a calculation according to Eurocode 3 is conducted as well, and the results compared.

The suggested design has similarities to the existing designs. It does however have some distinct differences that could lead to an elevated risk of corrosion of the feet and attached plate. In order to use the suggested design, it should be investigated whether this risk pose any issues or if it can be neglected.

Lastly, to make sure the new design is entirely manufacturable without increasing the costs too much, a dialog with the suppliers should be started. This is also to validate the price of the new design.

# 10 Conclusions

## 10.1 Development Process

The methodology of Ullrich and Eppinger gives a clear guidance in how to perform a product development project. However, it is concluded that the methodology is better suited for consumer products or products that more people encounter. Products such as the foot which this project revolves around, could use U&E but has to find other ways of gathering the raw data from the customer.

The development project would have benefited from early testing of critical requirements such as the structural integrity and load distribution in order to identify false estimations and misconceptions. The conclusion from this is that the development process of products with a load bearing purpose would benefit from an early calculation or simulation to verify the weak links in possible existing designs.

## 10.2 Design and Results

The suggested design keeps a lot of traits from already existing designs to facilitate an easy implementation. It would not require any changes in packaging and can replace already existing feet that use the swing attachment principle.

It was concluded that the most exposed bolt in the foot was the anchor bolt on the opposite side of the frame plate and applied load. The suggested design would decrease the usage of primarily the plate bolts up to 67%. The impact of the design on the anchor bolts was minimal. Further design suggestions should aim to minimise the usage in the anchor bolts.

Friction did not show to be of significant importance in the tested feet and preload had a negative impact on the usage. The preload raised the usage but not enough to become more exposed than the anchor bolt. New tests of friction and preload with a looser constraint would be good to validate the given results.

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