MASTER THESIS

Future body structure concept for HESS buses

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Year of completion:

2023

MASTER'S THESIS ASSIGNMENT

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Study program: **Master of Automotive Engineering**

Branch of study: **Advanced Powertrains**

II. Master's thesis details

Master's thesis title in English:

Future body structure concept for Hess busses

Master's thesis title in Czech:

Koncept konstrukce karoserie pro autobusy Hess

Guidelines:

Investigate todays Hess Co-Bolt structure at 2 axles, 3 axles and 4 axles buses.

Propose changes of the structure in order to:

- Reduce: assembly time, weight and number of parts
- Increase strength and Stiffness

Create a CAD concept for co-bolt 2.0 system incl. modular + scalable sub assemblies in CAD

Name and workplace of master's thesis supervisor:

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Name and workplace of second master's thesis supervisor or consultant:

Date of master's thesis assignment: **30.04.2023**   Deadline for master's thesis submission: **11.08.2023**

Assignment valid until: _____

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20/06/2023
Date of assignment receipt

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Abstract

In the automotive industry, there is nowadays a constant need to make vehicles lighter. This is no exemption for bus manufacturers, especially for the Swiss company Carrosserie HESS AG, which specialises in the production of electric buses. The patented CO-BOLT system, that they have been using for more than thirty years to make the body of their buses, has so far been able to meet all the necessary requirements regarding the strength and the weight of the structure. This allows for high loads on the roof, especially considering the weight of the high-performance batteries that are positioned on top of the body of their buses to maximise the interior space and thus, the comfort of the passengers.

However, as the need to save energy and produce the vehicles quickly becomes more present, HESS engineers are constantly looking for ways to improve their buses, especially by making the body lighter, stronger and faster to assemble. The aim of this thesis is to design a new CO-BOLT 2.0 model that could be used for HESS buses, by investigating the current CO-BOLT structure and finding innovative ways to optimise all these parameters in a way that keep the assembly cost efficient for the company.

After having identified that the main area for improvement in the current CO-BOLT system lies in the way in which the aluminium profiles that make up the bus body are connected to each other, a study of different concepts for new connections, inspired by existing ways of connecting aluminium profiles, was undertaken. Following this study, one solution was selected. With new connection parts made in aluminium and manufactured with CNC machining, this new way of connecting profiles saves assembly time and weight in the body and it also limits excessive displacement of the profiles when they are subjected to high loads due to the weight on the roof of the bus. These qualities make the use of these connections for the CO-BOLT 2.0 model a starting point for a possible evolution of HESS bus bodies and in the improvement of their qualities. However, it would require a little more research than what is studied in this thesis to create a new body design that is fully exploitable for the company.

Key words

Bus, Body, Aluminium, Lightweight, Strength, Connection, Manufacturing

Declaration of Authorship

I hereby declare that I have completed my thesis on " Future body structure concept for HESS buses" independently using literature and sources, and the references listed in the list of sources in the last chapter of this thesis.

Made in Bellach on: 11/08/2023

Preface

This master thesis has been conducted at Carrosserie HESS AG in Bellach (Switzerland) for 22 weeks from March to August of 2023. The project is the final part of the Master of Automotive Engineering (MAE) at the Czech Technical University in Prague (CVUT) and corresponds to 30 credits.

I would like to direct a special thanks to:

-Alex NAEF, CEO of HESS for letting me do this thesis in his company, which will undoubtedly have an extremely positive impact on my future career as an engineer.

-Jan WUNDERLICH, my supervisor at HESS for his continuous support throughout this project. His knowledge and experience in handling such projects truly helped me to stay on the right track and to complete this thesis.

-Marco FERRONI, as well as all the member of the engineering team from HESS, for taking the time to answer all the questions I had, especially about the design of HESS buses and about the use of the CAD software.

-Mijo JAZVIC, as well as all the members of the production team from HESS, for taking the time to explain all the details about the assembly of HESS buses.

-All engineers from supplier companies, especially Ryan CAO from Rp Proto, Luke SMOOTHY from Get it Made and Theres WILLIAMSON from Prétat, for giving me accurate quotes, as well as helpful advice about the manufacturing processes of aluminium parts.

-Lukas KAZDA, my supervisor at CVUT, for his permanent availability, giving me feedback and helpful advice about how to correctly perform a Master Thesis.

Contents

List of abbreviations and nomenclature

Abbreviations

CAD: Computer Aided Design

CFRP: Carbon Fiber Reinforced Polymer

CHF: Swiss Francs (1 CHF = 1.15 $ = 25.19 CZK in 2023)

CNC: Computer Numerical Control

DFA: Design for Assembly

DFM: Design for Manufacture

DFMA: Design for Assembly and Manufacture

DFX: Design for Excellence

FEA: Finite Element Analysis

Nomenclature

Symbol	Variable	Unit
E	Young modulus	Mpa
ρ	Density	g/cm^3
σ_y	Yield strength	Mpa
G	Shear modulus	Mpa
σ	Stress (by default the Von Mises stresses)	N/mm^2
δ	Displacement	mm
Ix, Iy	Area moment of inertia	mm^4
K	Torsional stiffness	mm^4
θ	Angle of twist	Rad
F	Applied force	N
T	Applied torque	Nm
L	Length of the profiles	m
a	Cross section height of the profiles	m
b	Cross section width of the profiles	m
M	Weight of the roof	kg
α	Coefficient of thermal expansion	$10^{-6}K^{-1}$
σ_{tu}	Ultimate tensile strength of sheet material	Mpa
σ_{br}	Bearing strength of sheet material	Mpa
σ_{su}	Ultimate shear strength of sheet material	Mpa
σ_{br}	Ultimate shear strength of bolt material	Mpa
t	Thickness of the sheet	mm
d	Diameter of the holes in the sheet	mm
W	Width of the sheet	mm
a_{max}	Critical acceleration	m/s^2

1) Introduction

1.1) Background

Energy consumption and environmental pollution has greatly increased recently, raising global concern because of the consequences on global warming. The road transport sector is one of most important sources of pollution, influencing both the environment and human health. Europe and many other countries in the world are adopting new laws or regulations governing the development and sale of all vehicles, to reduce CO2 emissions.

With these new regulations, the development of sustainable vehicles, especially electric buses, has greatly increased in numerous cities thanks to their characteristics of zero emissions and lower pollution noise which always contribute to the sustainable development of the cities, as buses tend to be now one of the most popular means of transportation. However, to allow electric buses to drive sufficiently long distances without charging, it is necessary for the buses to have batteries which can provide enough energy between the charging stations. Engineers are constantly researching ways to increase the battery capacity to extend the range of the electric vehicles. However, such batteries often take up a lot of space and greatly increase the whole weight of the vehicle which ends up increasing the energy consumption and thus compensating the benefits of these batteries by lowering the range of the vehicle. The solution, to avoid this problem, is to find other ways to reduce the weight of the whole vehicle so that more powerful and potentially heavier batteries can be installed without adding too much weight to the vehicle. Indeed, this problematic of the optimization of energy consumption is correlated to another problematic of making vehicles lighter for increasing energy efficiency as well as reducing production costs. Most particularly for buses, the reduction of weight often implies a detailed engineering study about its body, as it is estimated that the body frame accounts for 30% of the total weight of the bus in its overall frame structure.

The Swiss bus manufacturer Carrosserie HESS AG has needed to address these issues for many years, as they aim to establish themselves as a leading manufacturer of electric buses in Switzerland and abroad. Their patented CO-BOLT body model is an innovative solution to face these problems as the strength and the light weight of this body made with aluminium makes it possible to carry high loads on the roof with the batteries, which makes the whole bus a popular choice for city operators who are willing to extend the use of electric buses in their city.

Until now, HESS has used the same CO-BOLT model for the body of their buses for more than thirty years, which is proof of its great performance which stills holds up to this day. However, HESS engineers agree that this model nevertheless has the potential for further improvement. With new regulations on the safety demands and new environmental legislations, the demand for increased weight and strength for the bus body is a great engineering challenge that takes more and more importance today for all bus manufacturers. This would be no exception for HESS, as a further study in that field could bring a lot of benefits for the company. In addition, the growing success of HESS over the last few years, now delivering buses in all over the world, makes it even more challenging for the production team to ensure the construction and the delivery of all the buses in due time. Therefore, there is also a need for the buses to be faster and easier to assemble so that the production team can work more efficiently, and so that HESS can guarantee the production of all the buses without overworking the production team members. In conclusion, even though the CO-BOLT system of the HESS buses still has numerous qualities. There is both a desire and a necessity at HESS to look at the many ways in which this model could be optimized to make the bus both lighter, stronger, and faster to produce. If this study is successful, this would enable the company to maintain its position as a leader in the production of sustainable buses for the years to come.

1.2) Aim of the thesis

The aim of this project is to develop a new concept for HESS bus body which can keep all the advantages of the current CO-BOLT system, especially its possibility to carry heavy batteries on the roof, while optimizing the weight, the strength (and stiffness), and the assembly time of the whole bus body. This report will provide a study of the current bus body, both from the point of view of a member of the engineering team (studying the mechanical properties of the body) and from the point of view of a member of the production team (studying the assembly itself). The objective is to first generate different new concepts based on these observations and on the current solutions used by other bus manufacturers who must deal with the same issues. One of these concepts will then be chosen and will be the starting point to the development of the new body model, which will be called the CO-BOLT 2.0. Of course, even though it is not the main objective of this thesis, this project will have to be carried out in the way an engineer from HESS would do, considering its added value, especially regarding the costs so that the CO-BOLT 2.0 stays profitable overall for the company.

2) HESS and the CO-BOLT system

2.1) Presentation of HESS

HESS is a bus manufacturer based in Bellach, in Switzerland and founded in 1882 with production sites in Switzerland and Portugal. Their buses are widely used in Switzerland in all the major cities (Zurich, Geneva, Bern, Basel…) and in numerous countries of the world as well, especially France (Nantes, Lyon…) and Australia (Brisbane). HESS buses are electric driven using different body length, batteries, and charging concepts according to the needs of their clients. HESS also gives importance to the longevity of the vehicles they provide, with their lifecycle service contracts which make sure their buses remain functional during the contract by offering repair services in the case of collisions or even regular refurbishments.

As mentioned in the introduction, the body structure of the buses is made by the patented CO-BOLT system which is the source of many of the advantages of their buses, and which makes this company attractive in the bus manufacturing market, especially in Switzerland. Here is a summary of the best and most unique advantages their bus can offer according to the figure 1 below that can be found on the HESS website. [1]
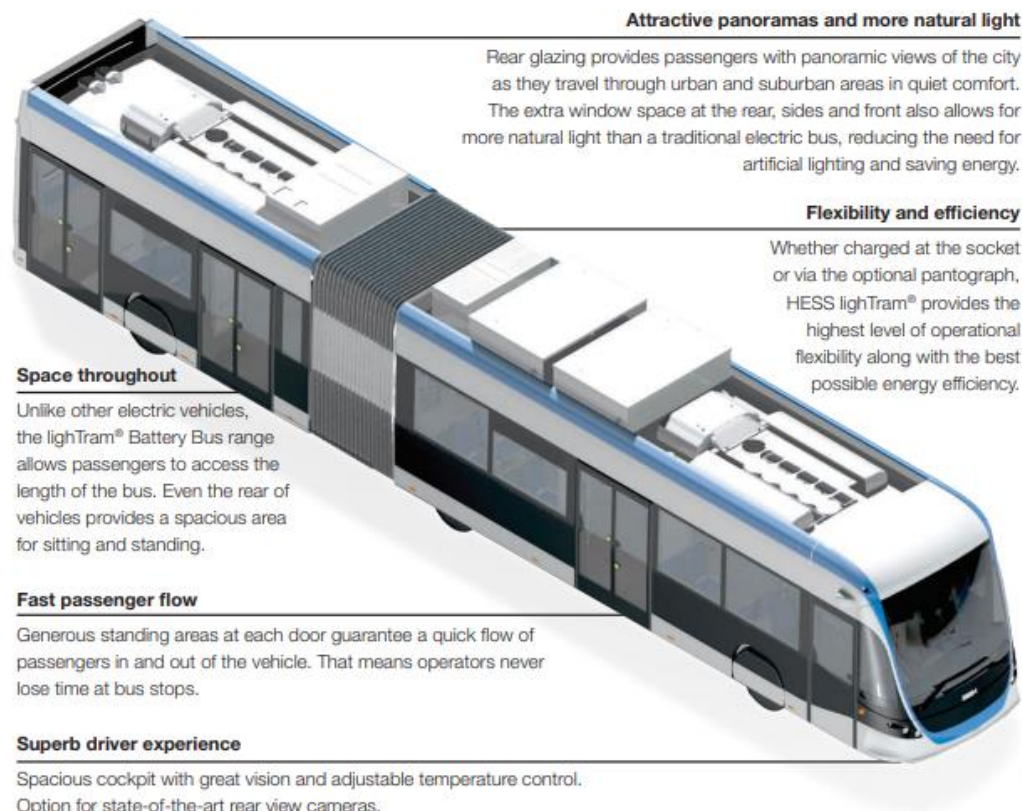

Attractive panoramas and more natural light

Rear glazing provides passengers with panoramic views of the city as they travel through urban and suburban areas in quiet comfort. The extra window space at the rear, sides and front also allows for more natural light than a traditional electric bus, reducing the need for artificial lighting and saving energy.

Flexibility and efficiency

Whether charged at the socket or via the optional pantograph, HESS lighTram® provides the highest level of operational flexibility along with the best possible energy efficiency.

Space throughout

Unlike other electric vehicles, the lighTram® Battery Bus range allows passengers to access the length of the bus. Even the rear of vehicles provides a spacious area for sitting and standing.

Fast passenger flow

Generous standing areas at each door guarantee a quick flow of passengers in and out of the vehicle. That means operators never lose time at bus stops.

Superb driver experience

Spacious cockpit with great vision and adjustable temperature control. Option for state-of-the-art rear view cameras.

Figure 1 : Summary of the main advantages offered by HESS buses

2.2) Presentation of the CO-BOLT system

2.2.1) The advantages of the CO-BOLT

The CO-BOLT system is an assembly of extruded aluminium profiles connected with aluminium corner pieces. The first main advantage of the assembly is that all the parts are joined together using mechanical fasteners instead of using adhesives or welding. This allows for a much easier reparability so that HESS can easily fulfil all the demands of their clients regarding the repair services. Also, using aluminium for almost all the parts, especially instead of steel, greatly reduces the whole mass of the vehicle and thus the energy consumption. The design of the profiles also contributes to the lightweight of the vehicle, each of the profiles having a hollow section which guaranties sufficient level of strength for the whole bus while greatly reducing the weight of the bus. Indeed, the whole assembly have been precisely engineered to keep the body strong and durable despite using a weaker material compared to steel, so that all the batteries, as well as air conditioning, break resistors and other high voltage components can be kept on the roof without generating big stresses and thus without risking damaging the body. Positioning the batteries on the roof instead of placing them closer to the chassis frees up an incredible amount of space in the bus, which brings a lot of comfort to the passengers by increasing the capacity of the bus, without increasing its overall size. This is also a great advantage regarding safety, as all the critical components are kept away from the parts of the vehicles which are more likely to be damaged in an accident. Here is a summary in the figure 2 below of all the advantages offered by the CO-BOLT system.
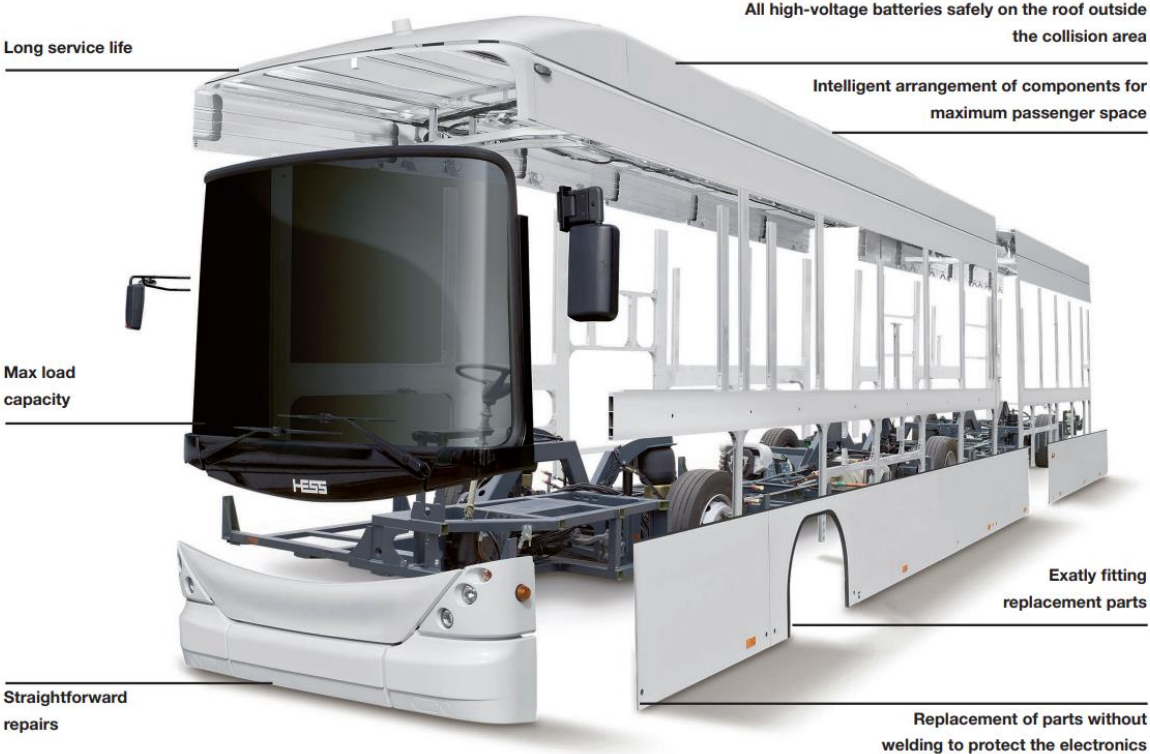

Figure 2: Illustration of the assembly of a HESS bus with all the qualities of its CO-BOLT body

Today, more than 20 000 buses around the world are using this CO-BOLT system. The bus comes in different models (2-axle, 3-axle, or 4-axle) according to the desired size of the bus by the operators. HESS is also constantly working in relation with these operators to ensure that the vehicles they provide meet their specific needs. They can adapt easily to the demands of their customers thanks to the great modularity of the system. The modularity is also one of the main qualities of the CO-BOLT. Indeed, the engineers from HESS always develop their product with parts that are independent to each other, each part "module" having their own features of functionality, which can be easily assembled to the other parts to create the bus body that will perfectly meet the needs of HESS customers. This also helps reduce product complexity and manufacturing costs.

2.2.2) The modelling of the CO-BOLT

All the parts making up the entire CO-BOLT system, as well as the assembly itself for the three different bus sizes (2-axle, 3-axle, and 4-axle) are stored as 3D files in SolidWorks. For the rest of the study consisting just of the optimization of the body, this body can be considered only as an assembly of the aluminium profiles and the connecting parts. The 3D model of the CO-BOLT (for the case of a 2-axle bus) that will be used for this project is shown in the figure 3 below.
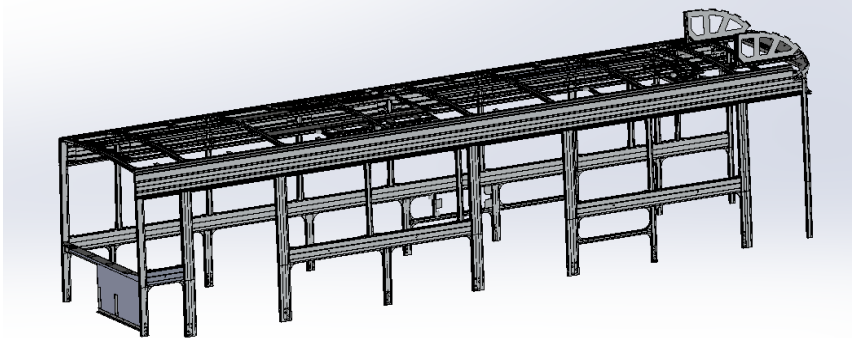

Figure 3: The CO-BOLT system modeled in 3D on SolidWorks

The materials are also specified in SolidWorks. Almost all the parts use aluminum but under different alloys that can affect the mechanical and physical properties of the parts. The whole bus body will be subjected to a few loads during the studies. These loads come from the acceleration and the deceleration of the bus in the three directions of space. These accelerations can generate huge loads because of the mass present on the roof of the bus with the batteries, as well as all the electrical equipment. Here is on the figure 4 below, a summary of the sources of weight that can be found on the roof of the buses.
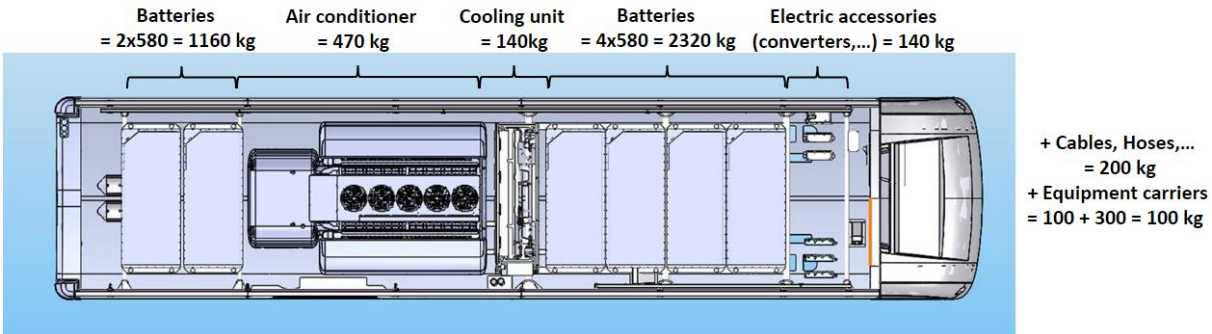

Figure 4: Details of the sources of weight on the roof of the bus

In the end, it can be considered that the total weight on the roof is about 4500kg. Three sources of acceleration can be considered. First is a vertical acceleration when the bus faces a bump at high speed which can be considered equal, in the most extreme cases, to 0,8g. This acceleration adds up to the gravitational acceleration to create a whole critical vertical acceleration of 1,8g. Then, there is the acceleration in the direction of the bus in case of an emergency braking which can be considered equal to 0,7g for the rest of the study. And finally, an acceleration perpendicular to the direction of the bus in case of an emergency steering can be considered equal to 0,5g. All these sources of acceleration will have to be considered together when making some dynamic simulation to ensure that the whole bus body will meet the strength requirements.

3) State of the art

Before diving into the study of the CO-BOLT system and of how it can be improved, it is necessary to have a full understanding of the design of a bus body made in aluminium and observe how other bus manufacturers managed to solve these problems of weight and strength. Indeed, various strategies have been used by different companies and can give some interesting ideas that will possibly be used later for this project.

3.1) The use and the choice of materials

3.1.1) The main materials used in the automotive industry

The first solution that is used in the automotive industry to make vehicles lighter and stronger is by choosing the right materials to make the body of the vehicle. Indeed, even though HESS almost only uses aluminium for to make the body of their buses. Various other materials can be used to manufacture the vehicles, each having their own advantages and drawbacks. Here is a quick presentation of the three most common materials that are found in the automotive industry:

-Steel: Various types of steel (mild steels, high-strength steels…) are used to manufacture structural components like chassis and body panels. It is a common choice of material for such parts thanks to the strength, durability, and cost effectiveness of all steel variations. This material is already used by HESS to produce the chassis of the bus, as the strength requirements are even more important in this area of the vehicle.

-Aluminium: This material is also often used for making structural components as an alternative to steel to reduce the weight of the vehicles thanks to its low density, improving the performance and the fuel economy of the vehicles. In addition to HESS, Nova Bus, a subsidiary of Volvo Group, has for example also used aluminium in the construction of the bus bodies to make their buses as sustainable as possible. Given the importance of the study of aluminium structures for this project, more details about this material will be given in a next part of this report. [2]

Figure 5: Picture of the body of the bus used by the company Nova Bus

-Polymer and composite materials: When there is a requirement for both a low weight and a high strength and durability, composite materials are used, especially carbon fibre-reinforced polymers (CFRP). This material is especially used more and more in the automotive industry as some bus manufacturers are even producing their buses only with carbon fibres. As an example, the bus manufacturer Ebusco now produces electric buses exclusively made from composite materials, which reduce the mass of the whole bus by 27% (9500kg) compared to a regular bus made of steel. This guarantees the bus's autonomy of up to 700km, making it extremely attractive on the market. [3]

Figure 6: Picture of the Ebusco 3.0, a bus model made with composite materials by the company Ebusco

As it can be seen on the figure 7 below detailing the composition of a car in the United States at different years, steel is now less and less used over the years in favour of aluminium and composite materials. This is due to the ever-increasing need to reduce vehicle mass to optimize energy consumption, while vehicles, particularly buses, are gradually moving towards zero-emission vehicles, using for a lot of bus manufacturers now, electric buses. In addition, as the automotive industry continues to evolve, there is ongoing research and development aimed at finding new innovative materials or making already existing sustainable material cheaper and thus more accessible to all the vehicle manufacturers. [4]
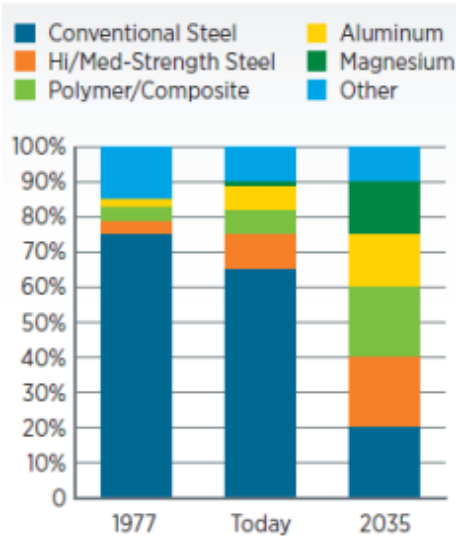

Figure 7: Diagram detailing the proportions of the materials used in the automotive industry at three different years (including a prediction for the year 2035)

3.1.2) Methodology for material selection

In automotive engineering, like in any other industry, material selection can be impacted by different parameters: weight, strength, stiffness, assembly methods, corrosion resistance, etc. Most of the time, the material is chosen to optimize both the weight and the mechanicals properties of the designed product. When having this requirement in mind, it is common to represent two of the most important properties of some different materials in a diagram, and to use an index to make the decision. One of the most common indices used is $\frac{E^{1/2}}{\rho}$, where E is the young modulus of the material, characterising its elasticity and ρ is the density of the material, characterizing its weight. Some variations also include $\frac{E^{1/3}}{\rho}$ and $\frac{E}{\rho}$. These indices give the best material option when the stiffness is prescribed, and the weight must be minimized. This is represented in the figure 8 below, where the three previously studied materials (steel, aluminium, and CFRP) are shown. In this case, when only looking at the material with the highest value of $\frac{E^{1/2}}{\rho}$, CFRP is the best material out of the three.
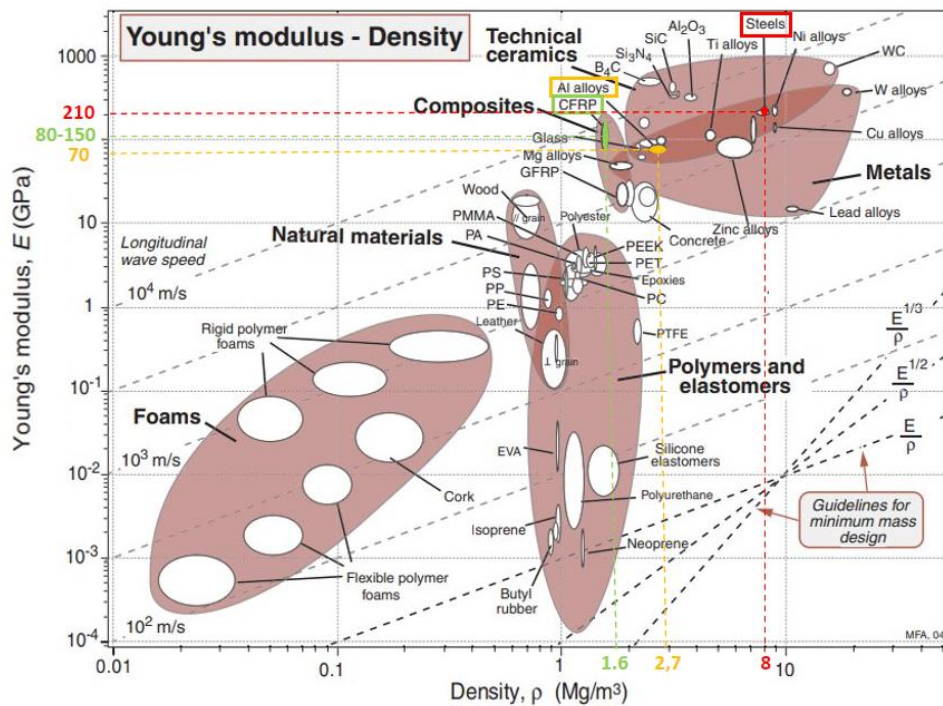

Figure 8: Diagram that illustrate the performance of different materials in terms of stiffness and density

In the last case, only the stiffness of the material is considered, but it is also possible to optimize the weight only according to the strength of the material. Here, the index that is mostly used is $\frac{\sigma_y^{2/3}}{\rho}$ (as well as $\frac{\sigma_y^{1/2}}{\rho}$ and $\frac{\sigma_y}{\rho}$) with σ_y being the yield strength of the material, characterizing its strength. The graph representing the yield strength of the most common materials according to their density is shown in the figure 9 below.
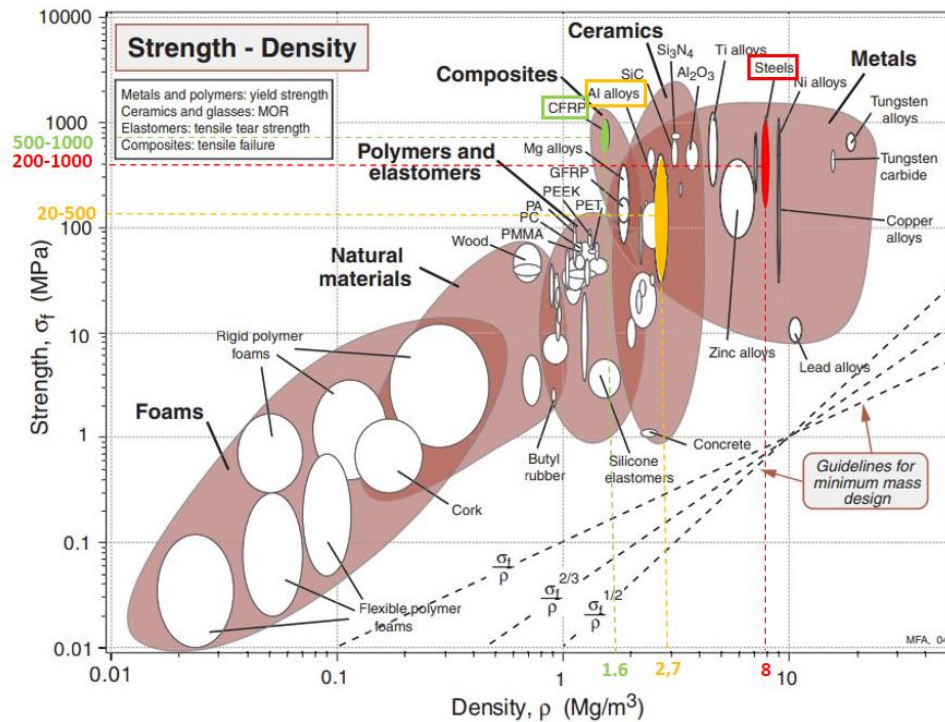
Figure 9: Diagram that illustrate the performance of different materials in terms of strength and density

In this case too, choosing a material according to the data on this graph gives the conclusion that CFRP is the best performing material. However, most of the materials have a wide range of values for the yield strength of the material. That is because the yield strength varies depending on the variation of materials chosen. For the case of aluminium for example, different aluminium alloys can have very distinct yield strength values. However, the alloy of an aluminium is not chosen exclusively based on its mechanical properties but also based on the manufacturing processes for example. That is one of the challenges of the choice of the right material, which must consider every parameter that can influence the choice at once. If only a choice according to the mechanical properties is desired by an engineer, it is possible however, to make the choice based on the value of $\frac{E^{1/2}}{\rho}$, as it is still the most precise way to find out the most performing material among some possible solutions, just based on the mechanical properties. [5]

When choosing other materials than aluminium (the material that HESS is currently using for the bus bodies), there are some important details that must be taken into consideration in addition to the strength and the weight. The first problem comes from the corrosion. For example, it could be the base of a concept to use carbon fibre to manufacture some parts for the body (thanks to the great mechanical properties of that material as seen above). However, if carbon fibre and aluminium are used together, there is potential for a type of corrosion known as galvanic corrosion or galvanic coupling. Galvanic corrosion occurs when two dissimilar metals or materials come into contact in the presence of an electrolyte (such as water), creating an electrochemical reaction that leads to accelerated corrosion of one or both materials. Carbon fibre is not a metal, but a composite material made from carbon fibres embedded in a polymer matrix. Aluminium, on the other hand, is a metal. When these two materials are in direct contact, an electrolytic environment can lead to galvanic corrosion due to the difference in their electrical potentials. A quick detail of these chemical reactions is shown in the figure 10 below. [6]
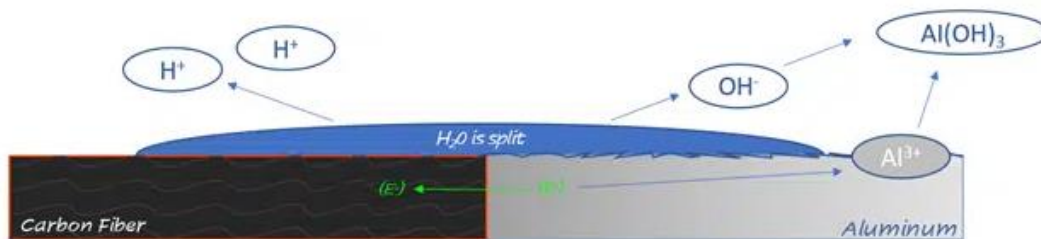
To prevent galvanic corrosion when using aluminium and another material, it is necessary, either to isolate the material by avoiding direct contact between the two materials or by applying protective coatings or other corrosion-resistant finishes, to the aluminium surfaces. These coatings can act as a barrier to the electrolyte and reduce the likelihood of galvanic corrosion. Also, when choosing to use a new material like carbon fibre, the company must ensure that this material fits all the regulations, especially fire-smoke regulations (to ensure the fire resistance properties of the material). In the end, these are all parameters that must be considered when choosing a material for some parts in the bus body, in addition to the already known parameters related to the mechanical properties of the materials.

3.2) Aluminium

3.2.1) generalities about the material

This part of the report will focus on aluminium, detailing its main properties. Even though some explanation about the use of aluminium have already been given in the previous parts, some additional knowledge about aluminium assemblies is necessary to get, as it is currently what makes the entirety of the HESS current bus bodies.

Aluminium is one of the most used materials in mechanical engineering, as it is the most abundant metal in the earth's crust. With a density three times lower compared to steel (2.7g/cm3 for aluminium and 7.83 g/cm3 for steel), this metal is especially famous for its light weight, as well as its resistance to corrosion and thermal conductivity (which is three times greater than steel), these combination of characteristics makes aluminium one of the most versatile material for a broad range of uses, especially in the transport industry where lightweight have become a major requirement for the vehicles as explained previously in this report. Indeed, there are huge environmental benefits to use this material, first for energy saving and because nearly 90% of automotive aluminium scrap is collected for recycling. Although materials like steel have better mechanical properties than pure aluminium, its strength can be increased with alloys. When choosing the right aluminium alloy, it is even possible to exceed the strength of the structural steels, even though it often requires high contents of alloying elements and thus cause a significant price increase because of the difficulty to manufacture. The most common alloying elements include Silicon, Iron, Magnesium, Zinc or Copper. The alloys are divided into two categories: wrought compositions and cast compositions. For both,

nomenclatures have been developed. A four-digit system for wrought alloys and a three-digit system for cast alloys is used to produce a list of composition families as follows. [7]
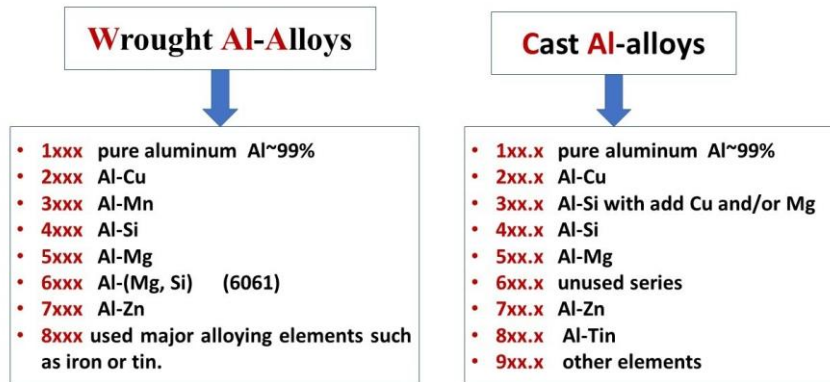

Aluminum Alloys Designation

Wrought Al-Alloys

- **1xxx** pure aluminum Al~99%
- **2xxx** Al-Cu
- **3xxx** Al-Mn
- **4xxx** Al-Si
- **5xxx** Al-Mg
- **6xxx** Al-(Mg, Si)   (6061)
- **7xxx** Al-Zn
- **8xxx** used major alloying elements such as iron or tin.

Cast Al-alloys

- **1xx.x** pure aluminum Al~99%
- **2xx.x** Al-Cu
- **3xx.x** Al-Si with add Cu and/or Mg
- **4xx.x** Al-Si
- **5xx.x** Al-Mg
- **6xx.x** unused series
- **7xx.x** Al-Zn
- **8xx.x** Al-Tin
- **9xx.x** other elements

Figure 11: Table detailing the different types of aluminium alloys

Especially, Magnesium and Silicon highly increase mechanical properties of the aluminium. Hence the alloys of the 6xxx family are the most common, especially for transport uses. This family is the most versatile family of alloy and can also be heat treated to enhance the mechanical properties. The most used alloy among this family is the aluminium 6082 which is the strongest alloy with the highest corrosion resistance. It is indeed used in the CO-BOLT system to produce the connecting parts like the brackets. The aluminium profiles of the body also use wrought aluminium from the 6xxx series (aluminium 6005 and aluminium 6106). Here, on the figure 12 below are all the properties offered by all the different alloying elements and their uses. Silicon is especially a popular alloy element for uses in the automotive industry. [8]
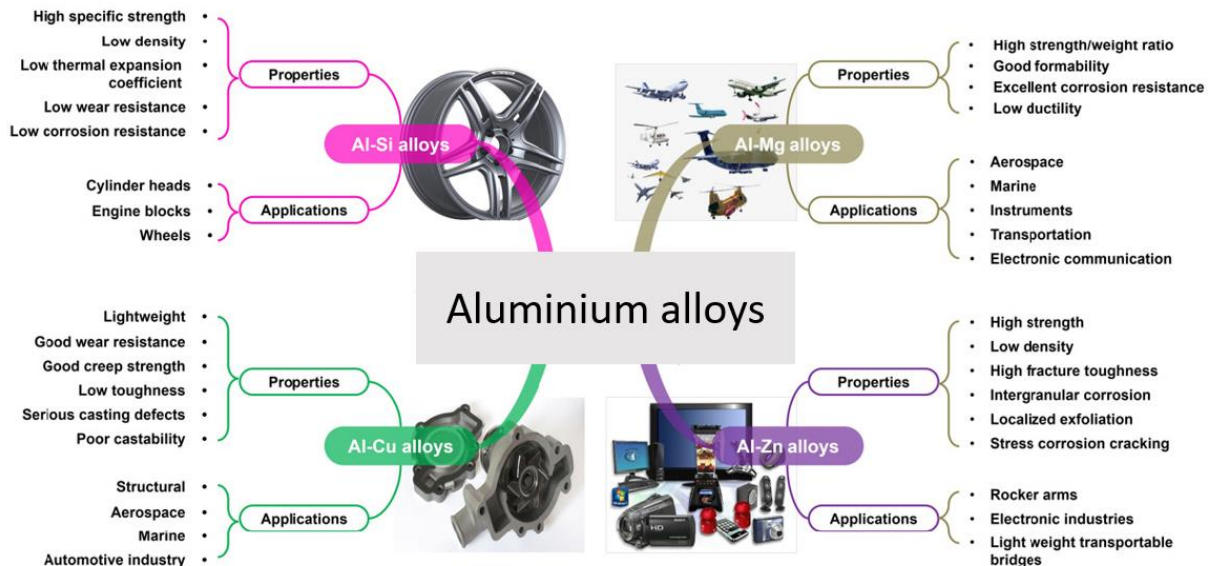

Figure 12: List of the possible uses for aluminium alloy, depending on the choice of the alloying element

3.2.2) Manufacturing Processes

Aluminium parts can be manufactured using various processes, each suited to a different type of parts with different requirements. Here are some common manufacturing processes for aluminium parts with examples for the uses of these processes in the automotive industry. [9]

Aluminium extrusion:

This process is specifically used to produce aluminium profiles such as rods, bars, and tubing. This is the process used to create the profiles of the CO-BOLT system. In this process, a bar of aluminium is heated to the deforming temperature of about 700 °C and then forced through a die with a specific cross-sectional profile depending on the desired cross-section of the profile. A ram then presses the aluminium through this die to create the aluminium profile as shown in the figure 13 below. The piece is then cut to the desired length. This process has a relatively low production cost and can create profiles of any length with any complex shape for the cross-section of the profiles. [10]
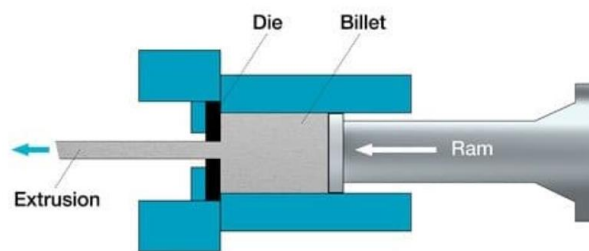

Figure 13: Illustration of the manufacturing process of aluminium extrusion

Aluminium machining:

The machining of aluminium involves the use of manual machining tools and equipment to shape the part into the desired form. Manual machining of aluminium is often used for small-scale production or prototyping. For bigger productions, CNC machining is mostly used where machines controlled by computers are used instead of using manual tools. During this process, the aluminum part is mounted on a machine and a cutting tool removes the material from the outer surface. The removal process is done according to the instructions given by the computer program. The machine follows theses instructions to perform the machining operations with great precision and consistency, until the aluminum parts acquire the required shape. Despite relatively high production costs (mostly due to a waste of material that can be important for certain parts), this allows for higher production speed and better product precision and finish. It is also a suitable production method when the part has a complex geometry that cannot be made efficiently with other manufacturing methods. [11]

Aluminium casting:

The casting process can be the most optimal way of production for certain parts with a specific geometry. It is done by injecting melting aluminium under high pressure into a steel mold. This process is illustrated in the figure 14 below. When the plunger is pushed upwards, it sucks the material into the

20

chamber and is then pushed with high pressure through the goose neck when the plunger goes down. The metal fills the empty cavity where it cools and hardens to make an aluminium piece with the shape of the mold. After separating the die halves, a product is obtained which is precisely formed with a smooth surface and generally requires minimal machining process afterwards. This whole process is called high-pressure die casting and is used by 70% of die casting manufacturers. Other die casting processes includes low-pressure die casting which can manufacture much larger and stronger parts, but on the other hand, the process is much slower, making it inappropriate when there is a high production demand.
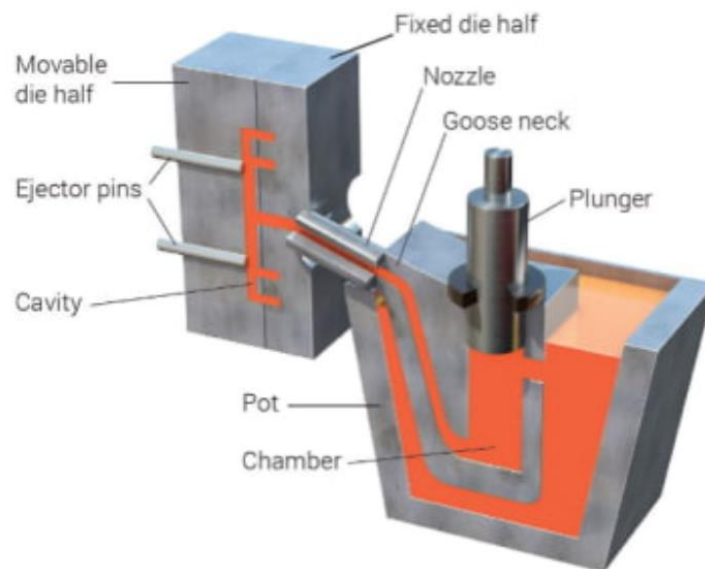

Figure 14: Illustration of the manufacturing process of high-pressure die casting

Overall, die casting is one of the most used manufacturing processes in the automotive industry and is suitable for producing large quantities as the production cost per unit decreases with larger orders. It can also easily produce complex shapes, hence its use in the automotive industry to produce engine parts for example. The main disadvantage with this process, however, is the limited use of materials. Indeed, only certain alloys can be used for this process (the ones that are called cast alloys, as seen in the previous part of this report) which are generally weaker than other wrought aluminium alloys and can, in consequence, result in a weaker structure. Some alternatives to die casting also exist like sand casting and investment casting (using a different type of mold), which can make the parts either cheaper or stronger, but they also have huge disadvantages when it comes to producing a high quantity of parts. [12] [13]

Aluminium forging:

Finally, aluminium parts can be forged using a hammer or a press to form the metal into a desired shape with mechanical force. Compared to the other processes, the finished parts are stronger and more durable because it exposes the metal to intense pressure, which straightens the grains and improves the mechanical properties. However, forging aluminium parts is often a time-consuming and costly process, especially for large production runs and when it comes to producing parts with complex geometries. One advantage, however, is that unlike machining, there is no waste of material which can be beneficial for the manufacturing cost of certain parts. This process is especially suitable in the automotive industry to produce pistons or wheels. The detailed process of a production of a car wheel with forging is shown in the figure 15 below. [14]
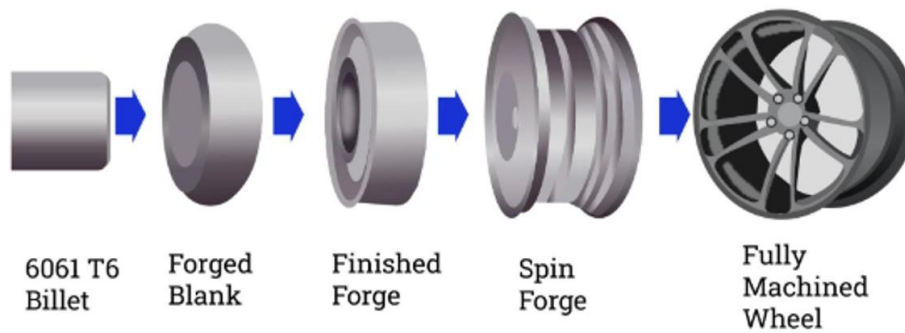
Regardless of the manufacturing process, it is common, for aluminium parts to apply surface treatment to make them corrosion resistant. It is often done by anodization. Type II anodizing (with sulfuric acid) is used to coat the surface of a part with an oxide layer to protect it from corrosion). Type III anodizing (or hard anodizing) produces a thicker oxide layer on the surface, adding wear resistance to the corrosion resistance achieved with Type II anodizing. It is sometimes important to precise that an anodized part is not an electrical conductor but that is not an issue for HESS buses bodies.

3.3) Aluminium profiles

In addition to the choice of the right materials and manufacturing processes, the solution for making a bus body stronger and lighter is sometimes simply to optimize the design of the assembly. Advanced computer-aided design (CAD) software like SolidWorks allows manufacturers to optimize the structural design of bus bodies, ensuring that the materials are used efficiently. This can involve using simulation tools to finds some points of improvement in the parts and make them stronger. For the case of the design of the CO-BOLT, the design of the profiles plays a huge role in the performances of the whole body and can affect its strength and its weight. To evaluate the strength and the weight of a single profile, there are some parameters that can be measured and then optimized to improve the design of the profiles. For the weight, the parameter is the area of the cross section of the profile. Indeed, with this area, it is possible to get the weight of any profile by multiply this value to the length of the profile and then to the density of aluminium (2,7 g/cm^3). To measure the strength of a profile however, there are more than one parameter to consider. All these parameters are connected to the moments of inertia of the cross section of the profiles. In fact, when a profile is subjected to a bending and a twisting load, the resulting displacement values will depend on the moments of inertia of the profile. For the case of bending (if the profile is fixed to one end and the force is applied right at the other end, as shown on the figure below), the maximum Von Mises stresses in a profile, as well as the maximum displacement when the profile is subjected to a force in one direction of space (in the direction of the x-axis for example which is perpendicular to the direction of the profile oriented in the same direction as the z-axis) are given by the formulas below.
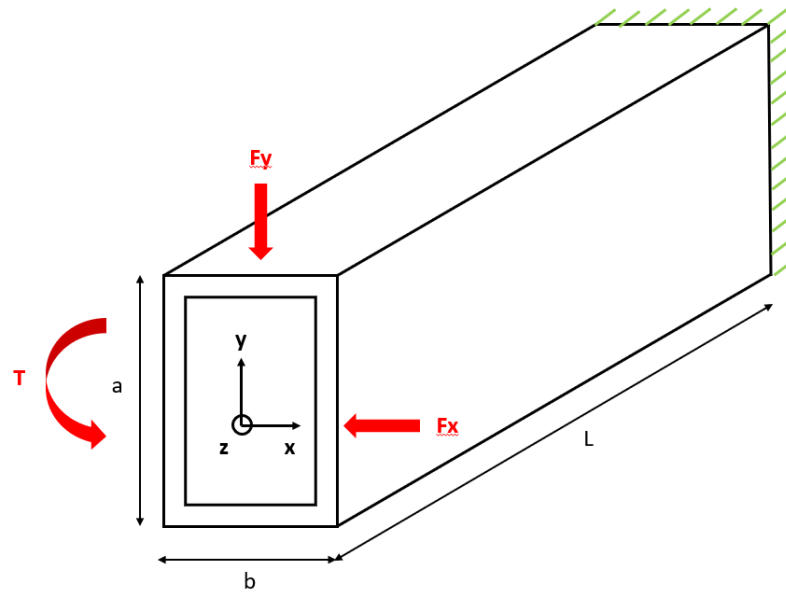
Figure 16: Illustration of the different parameters used to calculate the stresses and the displacement of a profile

$$\sigma max = \frac{Fx\,L\,b}{2\,Ix} \qquad \delta max = \frac{Fx\,L^3}{3\,E\,Ix}$$

These formulas remained unchanged if the force is in the direction of the y-axis (apart from Fx and Ix that become respectively Fy and Iy). For the case of twisting when applying a torque T, there are also some formulas giving the angle of twist θ of the profile:

$$\theta = \frac{TL}{KG}$$

All these formulas depend mainly on three parameters: Ix and Iy the two moments of inertia and K the torsional stiffness which is related to the polar monet of inertia. When some simple profiles shapes are studied (like rectangles or circles), some formulas are given to calculate the value of these three parameters based on the geometrical parameters of the profiles. However, because the cross-sectional shapes of the profiles used for the CO-BOLT system are quite complex, there are no simple formulas to calculate the moment of inertia. However, these values can quickly be found with CAD software like SolidWorks. That is the method that will be used to obtain the values of these three parameters. In the end, the objective when trying to optimize the performances of the profiles of the CO-BOLT is to maximise the value of the two moments of inertia, the torsional stiffness and to minimize the value of the cross-section area. With the right geometry, good values can be obtained for these profiles, which in the end will make the whole body even stronger and lighter. [15]

3.4) Aluminium assembly

For the case of an assembly of aluminium profiles, the choice of the material and the optimization of the profiles are not the only way of improving the performances of the structure. Indeed, many vehicles manufactures focused their study on creating innovative joining methods. There are many way profiles can be connected: from adhesive bounding to fastening methods, finding efficient methods of joining can also improve the structural integrity of the assembly and reduce weight.

3.4.1) Permanent joining

To begin with, it is important to know that, in addition the mechanical fasteners that HESS bus bodies are currently using, it is also possible to use welding, brazing, soldering and adhesives to combine profiles permanently. It will however be difficult afterwards to separate the components if there is a need for repair for example. That is why lots of manufacturer still prefer joining methods that offer customizability, using mechanical fasteners such as nuts, bolts, screws, and rivets to have a better degree of versatility when joining aluminium extrusions and for the possibility of disassembling. The advantages and disadvantages of joining methods with adhesives and mechanical fasteners are summarized in the following table. Given the importance of some off the requirements for the CO-BOLT system (especially its need for repairability), it justifies the choice of using only screws and bolts to assemble HESS bus bodies. [16] [17]

Requirements	Mechanical fasteners	Adhesives
Create a strong bond	YES	YES
The application process can damage the structural integrity of the material bonded	YES	NO
Require surface preparation	YES	NO
Is ready to use straight after application	YES	NO (curing time required)
Can offer fire resistance	NO	YES
Can require extensive training to apply	NO	YES
Is the most suitable to dampen vibrations	NO	YES
Is the most suitable to distribute strength	NO	YES
Can join dissimilar materials	YES	YES
Can result in excess waste which requires cleaning	NO	YES
Can corrode over time	YES	NO
Possibility to remove and replace easily	YES	NO
Low and Cost-effective method of bonding	YES	YES

Table 1: Summary of the advantages and drawbacks of mechanical fasteners (screws, rivets...) compared to adhesive bounding


Figure 17: Picture of three profiles permanently connected with welding

3.4.2) Non-permanent joining

Now, all the different ways in which mechanical fasteners can be used to connect aluminium profiles will be detailed in this part of the report. The first and most common type of connection is the use of brackets parts. This is the most basic method meant for 90 degrees connection. It is a simple and cost-effective connection in the way that it does not require any additional machining of the profiles. Another advantage with this type of connection is the flexibility and the adaptability, as these brackets can easily be placed anywhere on the profiles and moved to another location. This is especially convenient when there is a need for a modular assembly, like it is the case with the CO-BOLT. One of the disadvantages which is often mentioned with brackets is the aesthetic appearance, but it is not an issue if there are used in the CO-BOLT as the body is not a visible part of the bus and doesn't affect the customer appreciation. They can, however, take some assembly space. Of course, the bigger the part is, the stronger it will be, and the higher will be the maximum loads allowed on the connecting profiles. [18]
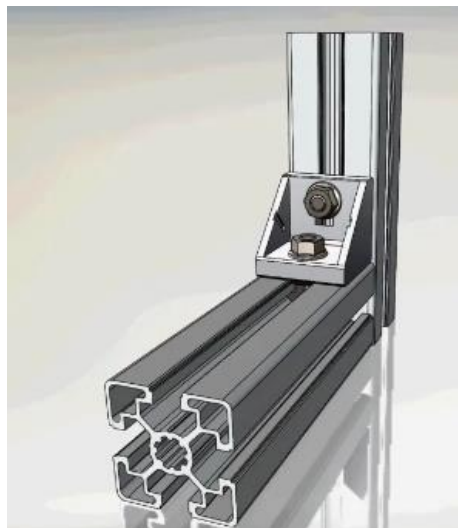
Figure 18: Picture of two aluminium profiles connected together with a bracket part

One common alternative method to the use of bracket parts is the use of connector sets. This is also a relatively basic joining method, as it limits the number of parts that must be produced and used to make a connection. Indeed, multiples bracket parts generally must be used for a simple connection with the bracket joining method whereas only one connecting part is necessary with this method. There is also the advantage that this part stays hidden in the assembly, which makes the connection more aesthetically pleasing and that they require no additional space. It is also compatible with both mechanical fasteners and adhesives, hence the popularity of this method of joining. Especially, developing connector parts is now quite common for bus manufacturers to make bus bodies, like it is the case for Mercedes who have already undertaken some research about the use of such connector for bus bodies. The figure 20 below shows how to adapt this method of joining to an assembly of profiles on a bus body. This method has also already been used by bike manufacturers like Bastion Cycle to connect the profiles of the bikes as shown on the figure 20 below (here the profiles are made with carbon fibre instead of aluminium however) to make the structure stronger and more durable. This could then be adapted to bus bodies as well, to have the same positive impact on the structure of HESS buses. [15] [19]

Figure 19: Picture of two aluminium profiles connected together with a connector set

Figure 20: Two systems using the connector set solution to connect some profiles. The Mercedes bus body on the left and the Bastion Cycle bike on the right

When researching joining methods for aluminium profiles, other different methods can also be found. For example, there is the method of using connector cubes. This takes inspiration from the connector parts that have been discussed above but adapt this solution so that the profiles connect to the node part only by means of a single screw as illustrated on the figure 21 below. Even though this connection only requires the use of one screw, it is still a great type of connection to withstand the forces exerted on the profiles, especially torsional loads. Of course, this connection also has the advantage of using a minimal number of parts (including the screws), which is a great solution to reduce the manufacturing time of the assembly. However, the main disadvantage is that it is necessary to form a thread inside the profiles with a thread forming tap. This method of joining would then not be possible to be use with HESS current body profiles. [20] [21]

Figure 21: Illustration of how these connector cubes can be used when using threaded profiles

If there is a necessity for the connection parts to stay invisible, then some methods of joining already exist and use very small and simple parts that connects to the profiles with screws and nuts as shown in the figure 22 below. Even though this is great to reduce the weight of the connection, it is not

an ideal solution when there are some important requirements regarding the strength of the assembly. Finally, connecting plates are also used sometimes as an alternative to brackets, the advantages and disadvantages of such connections are overall the same as for the connection with brackets. The use of either one of these two solutions depends on the rest of the assembly, as for example for the case of the CO-BOLT, some other parts like reinforcement plates are assembled on the side of the profiles, making this type of connection not optimal. [20]
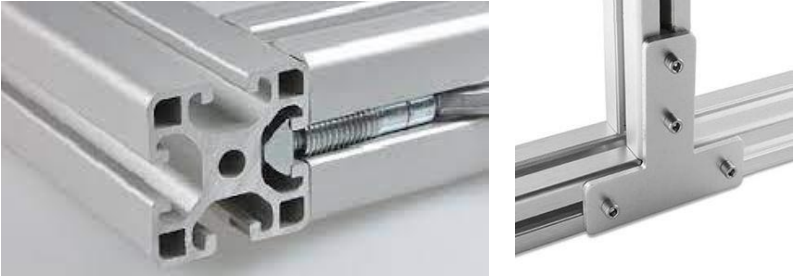
Figure 22: Picture of two other alternatives way to connect the profiles: one with a minimum number of big parts on the left and the other on the right with connecting plates

3.4.3) Assemblies with screws or rivets

Whatever the method is, when assembling some parts with mechanical fasteners (like connections between some profiles), it must always be checked that that the connection is strong enough to resist the high loads of the structure. An assembly of two parts tied with screws or rivets can generate stresses causing failure modes in four different ways. For each mode of failure, formulas can be found to estimate the highest load F acceptable depending on the parameters of the assembled parts (thickness, length, etc). That will be something to consider for future studies when designing a connection with screws or rivets. [22]

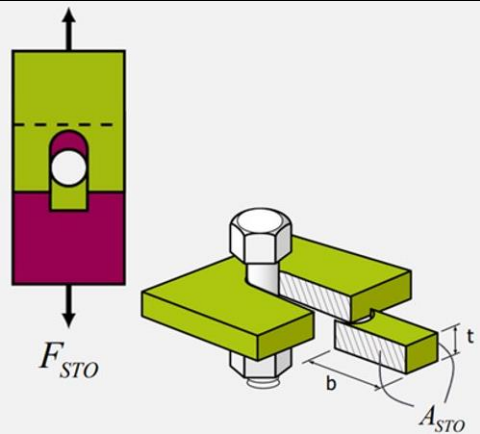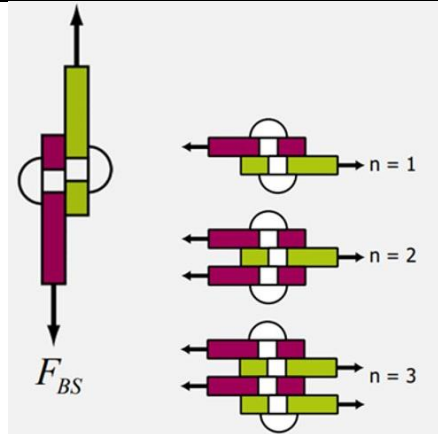| Net section failure:	Bearing failure:
$F_{NST} = A_{net} \times \sigma_{tu}$ With σ_{tu} the ultimate tensile strength of the material $A_{net} = t(W - n \times d)$ with n the number of fasteners along net section.	$F_{br} = A_{br} \times \sigma_{br}$ With σ_{br} the bearing strength of the sheet material $A_{br} = t \times d$

Shear tear out failure:	Bolt shear failure:
$F_{STO} = A_{STO} \times \sigma_{su}$ With σ_{su} the ultimate shear strength of the material $A_{STO} = 2 \times t \times b$	$F_{BS} = A_{BS} \times \sigma_{s,bolt}$ With $\sigma_{s,bolt}$ the ultimate shear strength of bolt material $A_{net} = n \times \dfrac{\pi}{4} \times d^2$

Table 2: Formulas detailing the maximum load admissible for all four modes of failure

4) The project

4.1) Analysis of the weaknesses of the current CO-BOLT system

The first step in improving the design for the CO-BOLT body is to identify the weaknesses of the current system to find some points for improvement. Because the objective is mainly to make the bus body resistant and simple to assemble for the production, this analysis can be divided into a mechanical analysis, based on the observations made along with the engineering team and an analysis of the production of the bus based on the observation of the full assembly process of the body with the production team.

4.1.1) Mechanical analysis of the CO-BOLT

The objective in this section of the report is to analyze where are the weak points in the bus body to find ways to improve its strength. The best way to do so is by doing FEA simulations (Finite Element Analysis). Simulating the whole bus body at the same time, however, is a complicated and time-consuming task. To keep the study simple, the simulations will be done only for small sections of the body. The profiles which are subjected to the most important loads are the vertical ones on the side panels, as they must support the load of the heavy weight on the roof. These are the one that will be tested. The following simulation will be made: two vertical profiles will be connected to one big horizontal profile like it is done for the CO-BOLT with the same bracket connection parts. The big horizontal profile will be fixed on its two ends. One of the vertical profiles (the one at the bottom) will also be fixed on its end. This fixation represents how this profile is normally fixed to the chassis of the bus. Finally, a load will be applied to the end of the last vertical profile to represent the load due to the weight of the roof. Based on the known values of the acceleration that generate the loads on the profiles (1.8g vertically, 0.7g in the direction of the bus and 0.5g perpendicular to the direction of the roof) the simulations can be done applying the loads shown in the figure 23 below.
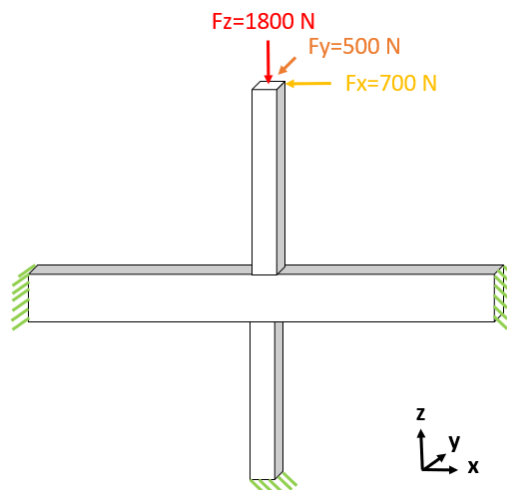

Figure 23: Explanatory diagram of the simulation, with the location and the values of the applied loads

Even though the values for the loads are not the same as the real ones. They still give an idea about how the structure behaves when it is subjected to proportional loads. Here are, in the figure 24 below, the results of this simulation, made with SolidWorks.
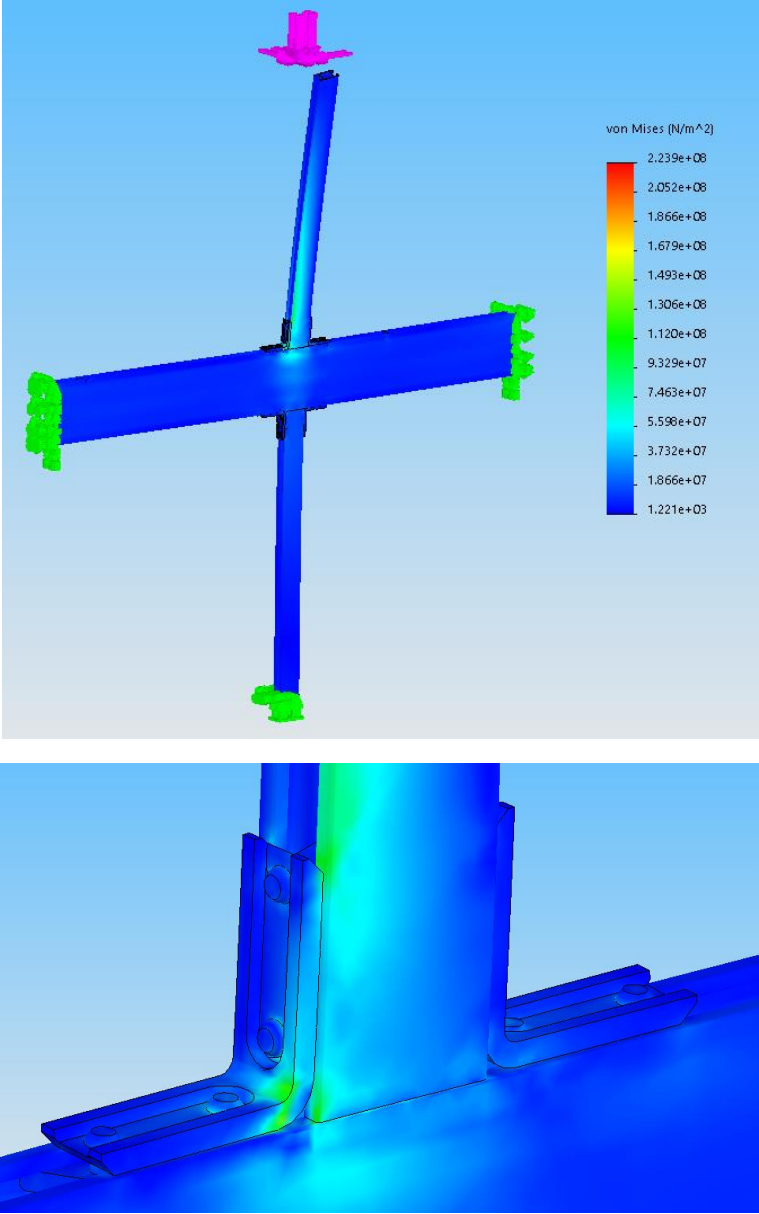

Figure 24: Results of the simulation including a zoom on the connection between the profiles

The first observation that can be made is that the stresses on the top vertical profile are getting higher the closer it is to the connection. In the figure 25 below is shown the evolution of the stresses along that profile.
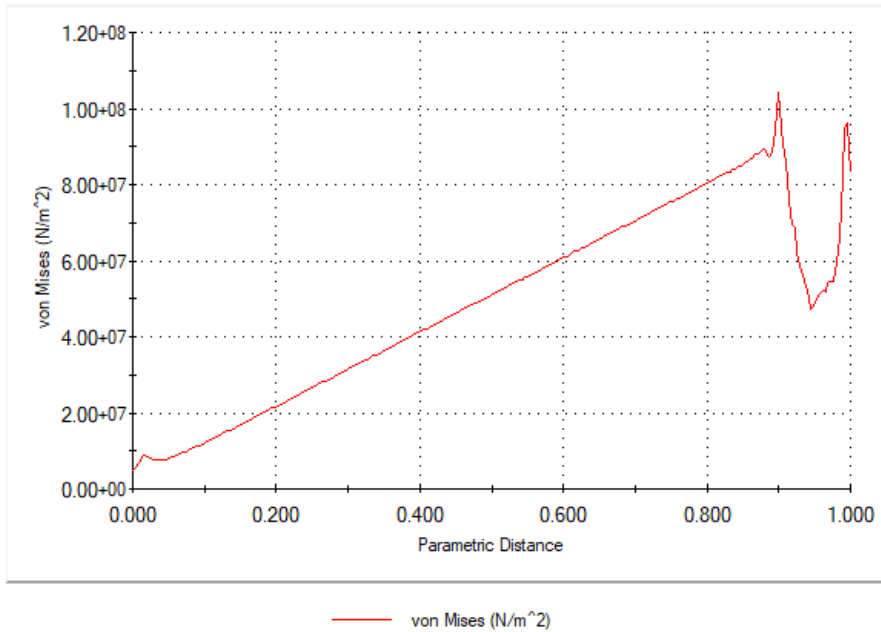
Figure 25: Evolution of the stresses along the top vertical profile

It can be observed that the Von Mises stresses increase proportionally along the profile until they reach the bracket parts where they change location and move to the brackets. This results in a high concentration of stresses close to the connection parts. A more detailed simulation done with other engineers at HESS show the consequences on these stresses on the deformations of the parts and eventually the rupture of those. In fact, the brackets used to make the connections are fixed to the profiles with screws and nuts. Because there are no holes in the profiles to avoid having to drill anything, the connection relies on the shape of the profiles to fix the parts with the strength of the screws. The figure 26 below illustrates how two brackets on the side are fixed to one profile in the centre of the picture below.
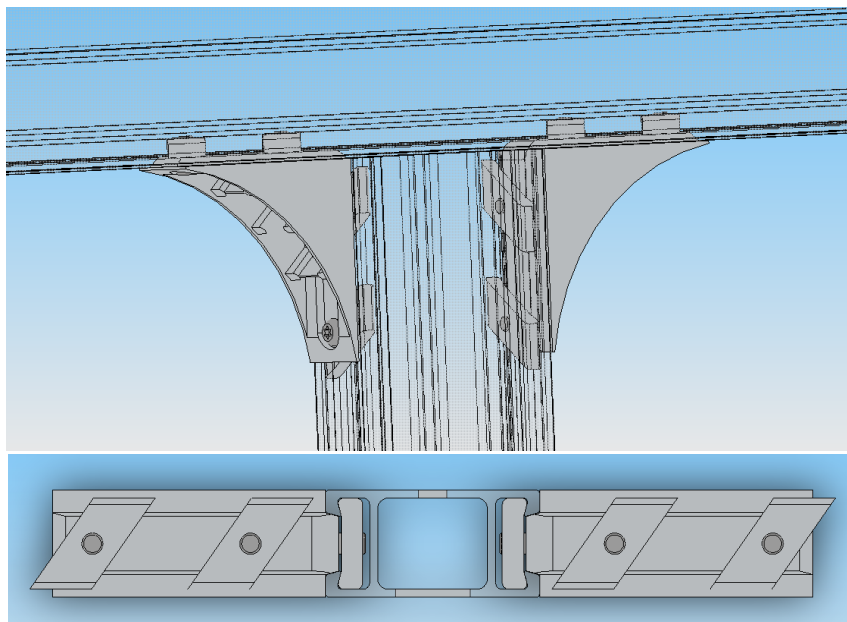

Figure 26: Pictures of a connection between the profiles of the body

In the figure 27 below, it is possible to see that when the assembly is subjected to high loads, some high deformations are generated on the profiles, which rips off the inside nuts that are used to fix the brackets parts to the profiles. These deformations are the consequence of the path of the load which have been highlighted in the previous simulation. Indeed, when a load is applied on the end of a profile, this load follows the path of this profile, creating stresses that increase the closer they get to the connection. When the load reaches the connection, it eventually goes into weaker areas, generating the huge displacement values that are found in these simulations.
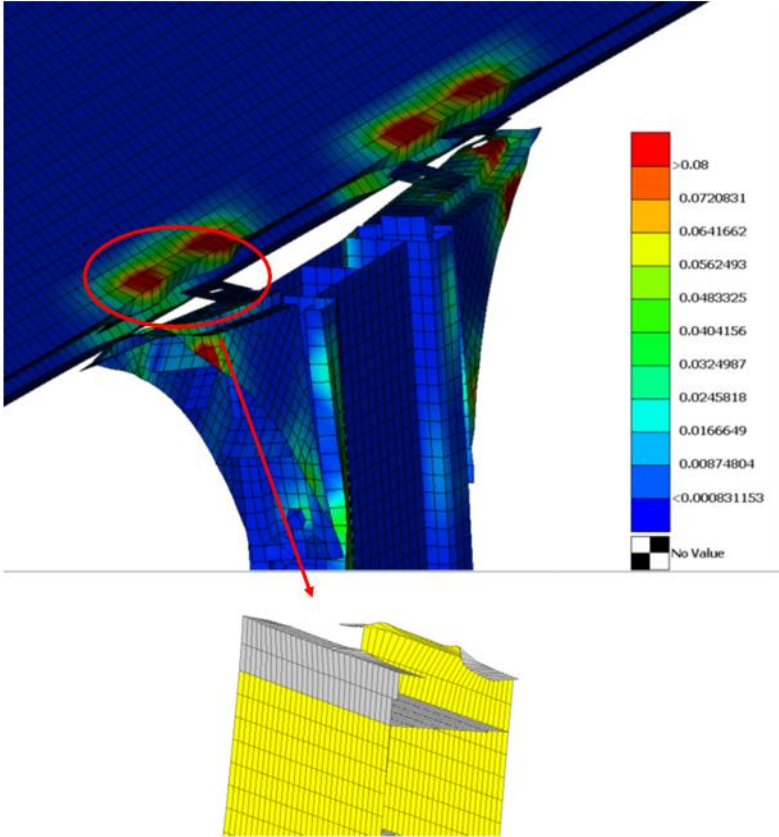
Figure 27: Location of the highest strain values in the connection itself and the effect of the high loads in the deformation of the profile

Finally, the conclusion can be drawn that the problem behind these high stresses comes from the way the profiles are connected to each other. Finding a better solution for the connection that can allow better paths of the loads and thus, distribute the strength in a better way could without any doubt be beneficial for the strength of the whole structure.

4.1.2) Analysis of the manufacturing of the CO-BOLT

When observing the full assembly process of the CO-BOLT system, some issues can also be identified. In the assembly of a bus body, the entirety of the roof, as well as the entirety of one side panel is assembled only by one operator which is responsible for positioning all the profiles correctly according to the drawings. The first difficulty comes from the fact that to perfectly respect the way the profiles are positioned, the workers at HESS must precisely measure the distance between the profiles with a tolerance of a millimetre. The angles between two perpendicular profiles must also be exactly of 90°, with a tolerance of 1°. This can be the source of long assembly times as it can sometimes be

difficult to position exactly these profiles to each other. Getting a bus body concept which could allow the production team to position instantly the profile without the need of precise measurement would then be a huge advantage as it could reduce the assembly time and the probability of errors. The long assembly time of the CO-BOLT also comes from method of connection itself. On average, to connect three profiles together like on the two pictures below, sixteen screws are necessary. Much of the time spent assembling the body therefore goes into screwing all these screws needed to guarantee a solid connection.

Figure 28: Picture of a connection between aluminium profiles of the body under different angles

There is, in conclusion, a lot of time that can potentially be saved in the assembly of the bus body by changing the way the profiles are connected. Such changes could become necessary for HESS as when demand of buses constantly increase, waste of time and errors are less and less tolerated.

4.1.3) General conclusion

According to both analyses, the conclusion can be drawn that the biggest point of improvements in the current CO-BOLT body lies in the connections. They can generate huge stresses values and longer production time. This is even more of a problem as the connections are present in high numbers in the whole body, so these disadvantages take on even greater importance for the body as a whole. Another global disadvantage of these connections is the excessive number of parts required to make one connection. For example, to make the same cross connections between three profiles as seen above, not only it can require up to sixteen screws but also sixteen nuts as well and more importantly, four bracket parts which makes a total of thirty-six parts just to make a single connection. Then if the whole bus body is considered, a really large number of parts are required to make the connections. The figure 29 below shows all brackets parts that are present in a 2-Axle bus body.
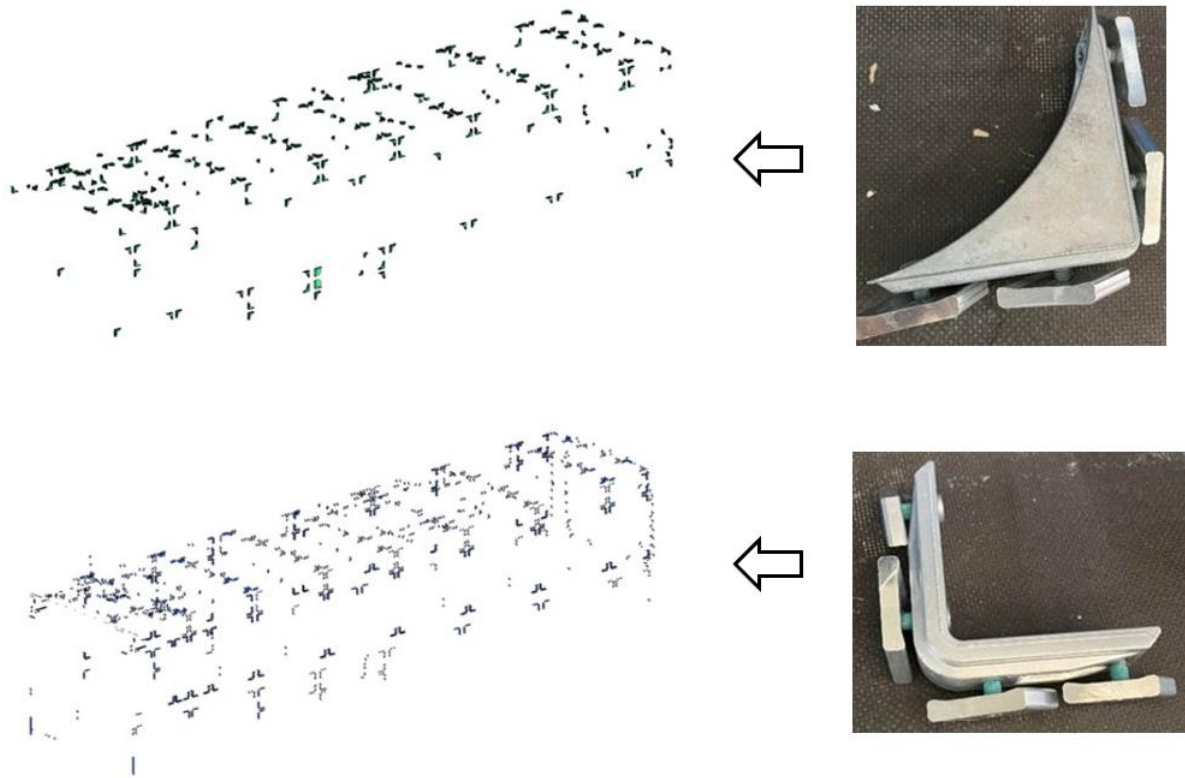
Figure 29: Illustration detailing the location of all the bracket parts in the whole bus body

In total, HESS bus bodies contain between 4000 and 8000 parts. When designing a product, it is never a good idea to have too many parts in the assembly as it makes it more complex and generate more disadvantages, especially for the production. Finding a simpler way to connect the profiles seems to be the best solution to make some great improvements to the bus body. This will be the focus of this project from now on.

4.2) The design phases

In mechanical engineering, product design involves going through a few phases to turn some ideas into a finalized product. What have been studied in the previous parts of this report serves above all to get the necessaries ideas and knowledge to perform the project. Now, is indeed the most critical part, so to ensure that no mistakes are made and that the requirements of the project are respected, it is necessary to follow the steps of product design in the right order. Here are these main steps:

-Conceptualization: First, all the ideas are gathered to generate some concept designs according to the requirements of the project. The design of the concepts doesn't have to be detailed for now, as most of them will not be used afterwards.

-Feasibility analysis: All the concept are then evaluated according to some specific criteria to check which are the designs that better meet the requirements of the project. The objective is to narrow down all the options and identify the most promising concept.

-Design: The preliminary design of the concept chosen during the feasibility analysis, is now further detailed. Some detailed CAD designs are also created with exact dimensions, materials, and manufacturing processes.

-Prototyping/Testing and validation: These are the last phases of the design of a product before general production. Some prototypes are made (generally with machining or 3D printing) and undergo various tests to precisely measure the performances. Based on the results of the testing, the design is then refined if necessary to optimize its quality. That is when the design is truly finalized, and the production can start.

For this project, the objective is only to advance to the stage of a detailed design of the solution. Creating some prototypes could be possible afterwards and should be a necessary step for the company, but for this will not be done in this thesis.

4.3) The different concept ideas

As explained in the previous part of the report, the first step in creating a new concept is to explore all the possible solutions which could help improve the CO-BOLT body. The conclusion has been made in the previous part of the report that the biggest improvements could be made in the connections between the profiles. When studying the different ways that the connections between aluminium profiles are made in various industries, different concept ideas of connections between the profiles can be generated by adapting this solution to a potential use for the body of HESS buses to create the CO-BOLT 2.0. It is important to explore all the different ideas to make a better comparison afterwards and justify the use of the future solution. The performances of the different solutions will all be compared to the performances of the CO-BOLT. To simplify the study, only three profiles of the body from the side panels will be considered, making a cross connection as shown in the picture 30 below.
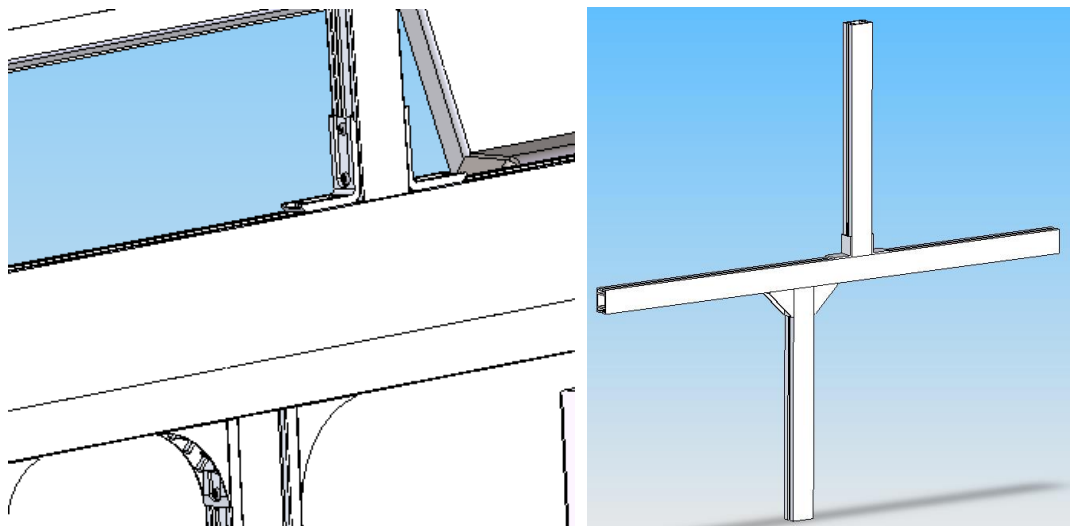
Figure 30: Picture of one connection between three aluminium profiles on SolidWorks. The current version used in HESS buses is shown on the left and the simplified version that will be used for this study is shown on the right

Because only the connection itself is the case of the study, the influence of the profiles will not be considered for now. All the profiles will be made approximately the same size and with the same mechanical properties for all the different designs. Here are, on the figure 31 below, six different designs that have been found as an alternative to the current solution used by HESS to connect the profiles.
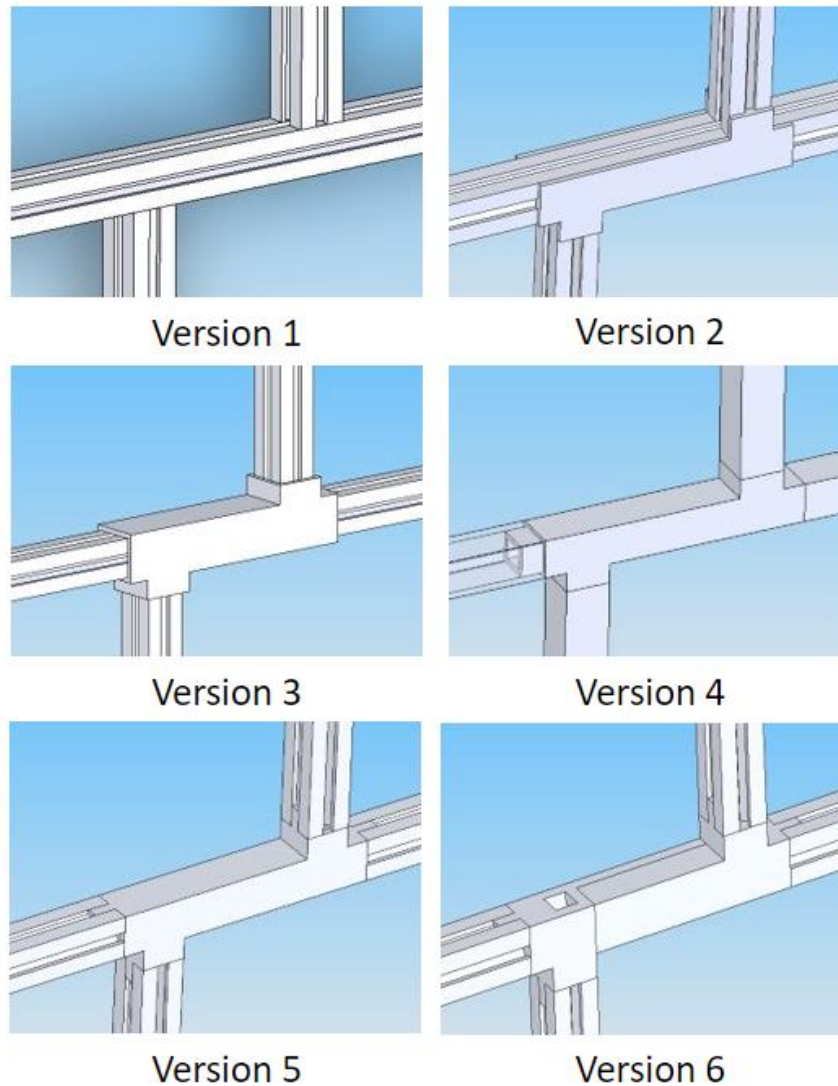
Figure 31: Pictures of all the six concepts of connection between the profiles in SolidWorks

Here is a brief explanation of the methods used to connect the profiles in all 6 versions:

-Version 1 uses a simple connector set like the one on figure 21 that uses few connecting parts and uses mainly screws to hold the profiles together. This makes the assembly simpler but may results in higher stresses.

-Version 2 uses the solution of the connecting plates like on figure 21 which is put on the side of the profiles.

-Versions 3, 4 and 5 all use connector sets to assemble the profiles. In consequence, the number of required profiles rises from three to four as the middle one is split between two smaller ones. In the first version, the profiles slide into the connection part whereas the opposite happens in version 4 as shown on the pictures. Version 5 is a combination between the previous two as the geometry of both the profiles and the connection part makes it possible so that the two parts can fit into each other. In the version 3 and 4, either adhesive bonding or fasteners can be used to hold the two parts together. The choice of using one or another for a specific version will make it split into two different subversions: versions 3.1 and 4.1 using glue and versions 3.2 and 4.2 using screws. In version 5, only mechanical

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fasteners will be preferred because of the small contact surface which may make it difficult to use glue for this connection.

-Finally, version 6 also uses a connector set like the three previous versions but this time, the part is connected to the profiles in the same way as a connector cube where one screw makes the connection thanks to a thread created in the centre of the profile. To make the assembly possible, the connection part must be split into two separate pieces so that all four profiles can be screwed without any problem. Each half is assembled first to two profiles by means of two screws before assembling with the other half (connected to the two remaining profiles), either with mechanical fasteners or adhesives to create an assembly of four profiles. Here is, in the figure 32 below, a more detailed picture of this whole assembly with one of the halves set in transparent to clarify these explanations.
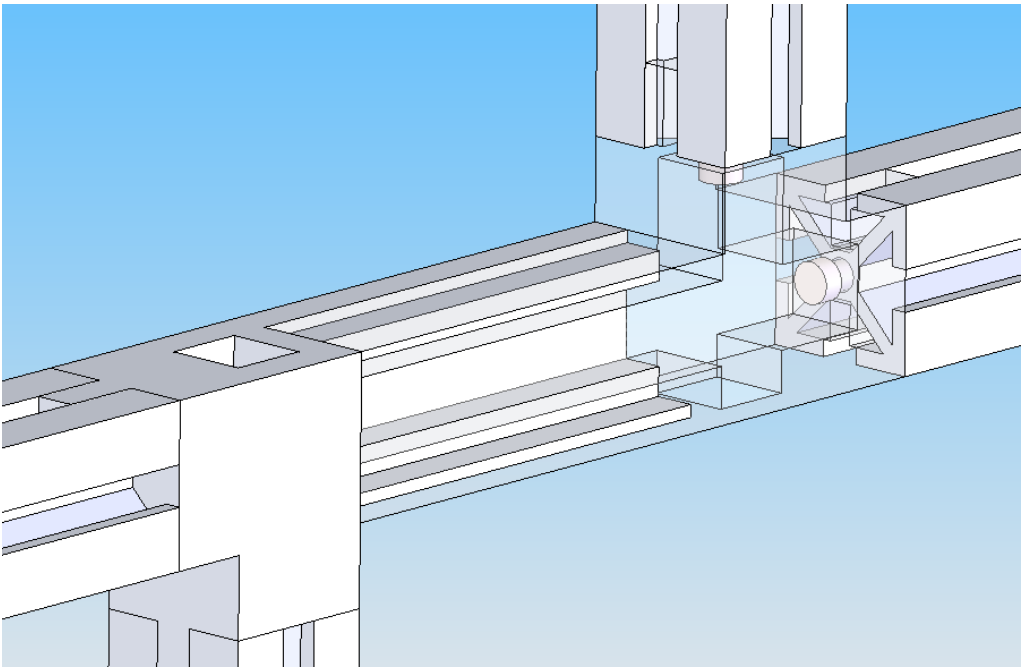

Figure 32: More details about the sixth concept design, with one of the two halves of the connection put in transparent

Here, different sub-versions will also be made depending on the way the two halves are fixed together. One simple cross connection between four profiles can be assembled in four different ways. For these fixations, glue is used in 6.1, rivets in version 6.3 and screws in version 6.2 and 6.4. The difference between the last two versions is the position of the screws. Two screws are placed horizontally in version 6.2 and one bigger screw is positioned diagonally in version 6.4.
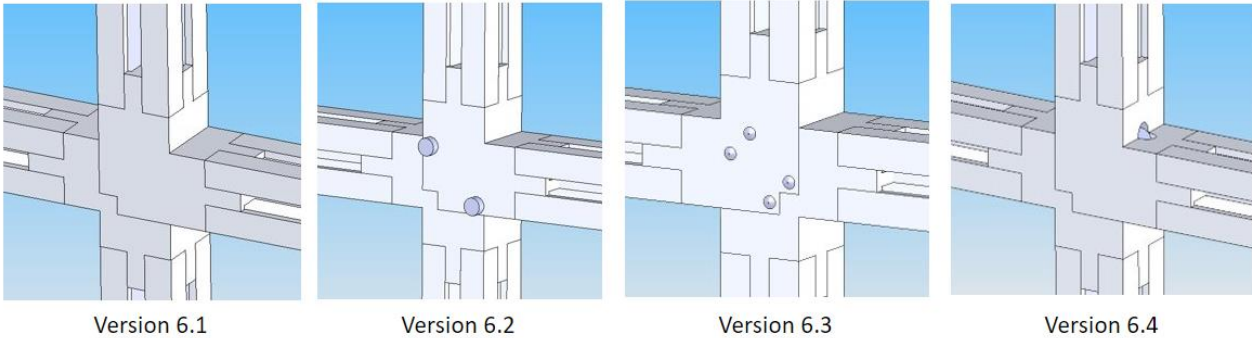
| Version 6.1 | Version 6.2 | Version 6.3 | Version 6.4 |

Figure 33: Pictures of the four subversions for the version 6 of the connection

It is important to precise that the number of screws or rivets that must be placed was chosen using the formulas of the failure mode for mechanical fasteners. Indeed, considering that the highest loads come from the weight on the roof when the vertical acceleration is at the highest (1.8g), the maximum loads applied on the connections will be the following:

$$F_{max} = a_{max} \times M$$

With $a_{max} = 1.8g$ (the critical vertical acceleration) and M the weight of the roof applied one vertical aluminium profile. This weight consists of the weight of all the electrical equipment and the batteries, which have already been estimated at 4500 kg, and the weight of the roof itself which is approximately 500 kg. Knowing that the right and left side panels consist of maximum of 18 vertical profiles, it can now be estimated that $M = \frac{5000}{18} = 280\ kg$. If a safety coefficient of 2 is also taken in consideration, the mass M will then be equal to 550 kg. Then the connection must be capable of supporting a maximal load:

$$F_{max} = 1.8 \times 9.81 \times 550 = 9,8\ kN$$

	W	d	t	n	b
Ver 6.2	40	6	6	2	6
Ver 6.3	40	5	4	4	6
Ver 6.4	20	8	10	1	10

Table 3: Summary of the geometrical parameters for all three subversions of version 6 using mechanical fasteners. All the lengths are in millimetres

Using the parameters in the table above for each version and considering the following approximate values, using aluminium for the connection parts and steel for the screws and the bolts:

$$\sigma_{tu} = 300\ Mpa \qquad \sigma_{br} = 300\ Mpa \qquad \sigma_{su} = 180\ Mpa \qquad \sigma_{s,bolt} = 250\ Mpa$$

The following maximum loads are obtained for the connection with each version (Version 6.3 has the values of the maximum loads multiplied by two, as two rows are rivets are used in the whole connection):

	F_{NST}	F_{BR}	F_{STO}	F_{BS}
Ver 6.2	50.4	10.8	13	14.1
Ver 6.3	48	12	17.2	19.6
Ver 6.4	36	24	36	12.6

Table 4: Maximum admissible loads (in kN) for all three subversions

In the end, with the chosen parameters for the design, all the values for the critical loads are greater than 9.8kN which means that all these versions have no risk of breaking because of the joining method.

4.4) The decision matrix

To choose the optimal solution between all the different designs, the pros and the cons must be established for all of them. The best way to do so is by using a decision matrix. A decision matrix is a common way to make a choice between different options. This is done by selecting a list of requirements which are then given a weight depending on how important they are for the project. Following this, each option is evaluated so that a score from 0 to 5 can be given to each of them for all

the requirement (5 means that the design totally meets that requirement and on the other hand, 0 means that it doesn't). In the end, after adding up the score for each requirement, the solution with the highest score will be the one chosen for the rest of the project. It is also important to precise that the solutions can always be improved regarding a specific requirement. For example, the strength/weight ratio for one solution could be made better by precisely optimizing the geometry. However, at this stage of the project, only a concept is studied and a detailed analysis of the design to make the structure as efficient as possible will follow, but only after choosing one specific concept idea among the many designs proposed. Here are, in the following section of the report, all the requirements that the different versions listed above will have to meet, the solution that better meet all these requirements will be the one which will be chosen.

4.4.1) Detailed description of the requirements:

1) Strength/Weight ratio:

The first requirement will be one of the most important for the rest of this study: for each solution, the weight and the strength will be measured and then be combined as a strength/weight ratio. Each solution will then receive a grade depending on how good this ratio is. The weight and the strength are measured together as these two parameters often depend on one another: especially, a part can always be made stronger by increasing the value of the geometric parameters like its thickness but will result in a greater or lesser increase in mass and therefore potentially a poorer strength/weight ratio. The weight can be easily measured on SolidWorks with the Measurement tools. To test the strength of the structure however, some dynamic simulation will be made. An assembly of four profiles will be considered with a structure and subjected loads similar to the ones used for the simulations done during the mechanical analysis of the CO-BOLT. Appling these loads for all concept design will provide a comparison for the strength of all the profiles. The measured value for the strength/weight ratio will then be the value of the weight of the assembly (in kg) multiplied by the maximum stress measured in the dynamic simulations. The lower this value will result, the better the strength/ratio will be obtained and so the best grade will be given to the design. For every design concept, even though some profiles may have different cross section shapes for assembly reasons, all the profiles will have the same moment of inertia and the same torsional stiffness to study only the influence of the different types of connections. Moreover, aluminium will be the material used for all the parts as only the design of the part is studied for the moment. The choice of the material will be the subject of a future study.

2) Assembly time

Assembly time is another important requirement to guaranty a fast production of the CO-BOLT bus bodies. The main cause of long assembly times is caused either by the curing time when using adhesives or the screwing time when using mechanical fasteners like screws. When using mechanical fasteners, it can be considered that the assembly time is approximately proportional to the number of screws that must be installed. The design versions using glue will receive the lowest score because of the curing time which is much longer in comparison to the screwing time of any other design concept. It will be considered that no mistake is made by the production team when assembling the parts, the probability of mistakes for each part is covered by another requirement.

3) Assembly complexity

The complexity of the assembly is another parameter that can influence the manufacturing time of the bus bodies. It means how hard the assembly is to make for the production teal. It is an indicator of the variability of assembly time, as a complex assembly may result in more mistakes by the production and a lower quality in the final product. Simple parts to assemble also brings more comfort to the production team and an overall better general satisfaction, which may in the end, also brings motivation for the worker to assemble faster. The evaluation for assembly complexity remains subjective as there is no precise indicator to estimate it. However, for each design, it can be possible to list the possible defects which can have an impact on the difficulty of assembling the parts together. For example, a connection which put the profiles immediately in place with no need of precise measurements (which is not the case with the current CO-BOLT model where the production team must take time to position the aluminium profiles together) will greatly reduce the difficulty to assemble the body. Also, a solution which involves drilling some parts, for example to put some screws will make it also more challenging for the workers as drilling also implies precise measuring and using of the tools. Based on these observations, it is possible to give each solution a grade from 0 to 5.

4) Parts complexity

The parts complexity refers mostly to the geometry of the parts that are used to make the connection. The main disadvantage of having parts with complex geometry will be the increase in the manufacturing costs to produce the parts. Theoretically, it could be possible to get an objective indicator of this complexity by getting an estimation of the manufacturing cost for all parts. But because it would take too much time for the duration of this project, the grade will be given only based on a subjective observation.

5) Modularity

Even though the study for the decision matrix involves a simple cross connection between four identical profiles, it is important to consider that the whole CO-BOLT bus body includes many different profiles and connections (some between four profiles and some between three profiles for example). The idea behind the concept of modularity is to determine whether it is necessary to design different parts for every one of these connections or if it can be possibly adapted to fit every one of them. The evaluation of this requirement is normally only a binary observation about whether yes or no, the concept is modular, but it is still possible to add a subjective estimation with intermediate grades if the design is not modular by itself but could be made modular with some improvements on the design.

6) Number of parts

As the title suggests, this requirement gives a grade based on the number of parts (a lower number of parts required to make a connection will give a better grade to the concept design). Indeed, as mentioned previously, the objective when designing an assembly of parts is always to minimize the number of parts used, as too many parts often increase the assembly time and the probability of mistakes. This is based on an objective observation of a connection with three profiles and a connection with four profiles (the average of the number of parts in the two assembly will be the indicator to give a grade to the design version).

7) <u>Repairability</u>

One of the important requirements of the CO-BOLT system is its easy repairability. As mentioned previously, it is important for HESS that their buses remain functional throughout their lifetime, with refurbishments and repairs if necessary. To guarantee this, the bus must not only be easy to assemble, but also easy to disassemble. A glued assembly will immediately give a bad grade to the design regarding that criterion as it makes the repairs difficult. That is the reason why HESS today prioritize mechanical fasteners as they give a huge importance to this requirement. Just like for the modularity, the evaluation of this requirement should be made based on a binary decision but because all the design are not yet optimized perfectly, a subjective observation can be considered to possibly give some intermediate grades between 0 and 5 to some concepts.

8) <u>Adaptability with the CO-BOLT 1.0</u>

If HESS chooses to put into service new buses with the CO-BOLT 2.0 using the new design for the connection of their profiles, all the buses currently in service would still stay the same using the CO-BOLT 1.0 model for some time. However, in case one of these buses must be repaired, it would be ideal that the parts used in the new design could also fit with some of the parts of the current design (especially with the current profiles). If not, the repairs would take much more time and will be a challenge for the company. The lowest grade would then be given in case that the whole body would have to be replaced even though only the connections require a repair and a high grade will be given if the solution can adapt to the current parts of the CO-BOLT system with potential intermediate notes just like requirement 5 and 7.

9) <u>Aesthetics</u>

The question of the aesthetics is a requirement evaluated based on a subjective observation which is still considered in mechanical design projects. For the case of the design of a bus body, it is not the most relevant as the passengers in the bus don't see that part of the assembly. It still however must be considered in the decision matrix like any other requirement.

10) <u>Compliance with ECE regulations</u>

This is a mandatory requirement that ensures that the bus body respects the ECE regulations relative to the mechanical resistance of the bus body structure. All design concepts should ensure that the whole bus has all these regulations validated.

4.4.2) Summary of the requirements

Requirement n°	Requirement	Unit	Ideal value(s)
1	Strength/Weight ratio	$kg \times N/mm^2$	Lowest
2	Assembly time	sec	Lowest
3	Assembly complexity	Subjective	Easy to assemble
4	Part complexity	CHF - Subjective	Lowest
5	Modularity	Binary - Subjective	YES
6	Number of parts	Units	Lowest
7	Repairability	Binary - Subjective	YES
8	Adaptability with Co-Bolt 1.0	Binary – Subjective	YES
9	Aesthetics	Subjective	Aesthetically pleasing
10	Compliance with ECE regulations	Binary	YES

Table 5: Summary of all the requirements the connection must respect and the criteria to evaluate them

4.4.3) Choice of the final design

Now that all the requirements have been established, the second step is to weight all of them according to their importance. The best way to do so is by completing a preference matrix where all the requirements are compared side-by-side to find out the value of the weight. Here is in the figure 34 below, a table that compares the importance of every requirement. Each of the yellow cells correspond to a comparison between two requirements. The one that gets the most importance for the case of this project gets its number written in the cell.

No. Vertical	Requirements	Strength/Weight ratio (1)	Assembly time (2)	Assembly complexity (3)	Part complexity (4)	Modularity (5)	Number of parts (6)	Repairability (7)	Adaptability with Co-Bolt 1.0 (8)	Aesthetics (9)	Compliance with ECE regulations (10)
1	Strength/Weight ratio										
2	Assembly time	1									
3	Assembly complexity	1	2								
4	Part complexity	1	2	4							
5	Modularity	1	2	3	4						
6	Number of parts	1	2	6	6	6					
7	Repairability	1	2	3	4	7	6				
8	Adaptability with Co-Bolt 1.0	1	2	3	4	5	6	7			
9	Aesthetics	1	2	3	4	5	6	7	8		
10	Compliance with ECE regulations	10	10	10	10	10	10	10	10	10	

Figure 34: Extract of the preference matrix justifying the weight given to each requirement

The objective in the end is to give a weight to all these requirements out of 100. To do so, all the occurrences of the requirement are counted and divided by the total number of occurrences for all requirements (which correspond to the number of yellow cells: 45). For example, the requirement n°1 (strength/weight ratio appears eight times in total so its weight will be the following:

$$W_1 = \frac{8}{45} \times 100 = 18$$

Doing the same for all ten requirements gives the following table:

Requirement n°	Requirement	Weight (/100)	Rank
1	Strength/Weight ratio	18	2
2	Assembly time	16	3
3	Assembly complexity	9	6
4	Part complexity	11	5
5	Modularity	4	8
6	Number of parts	3	4
7	Repairability	7	7
8	Adaptability with Co-Bolt 1.0	2	9
9	Aesthetics	0	10
10	Compliance with ECE regulations	20	1

Table 6: Summary of the weight of all the requirements

Now that a weight has been assigned to every requirement, it is possible to evaluate each design concept based on these requirements with a grade from 0 to 5. In the end, each version of the design will receive a score which will correspond to the sum, for all requirements of the grade multiplied by the weight of that specific requirements. The full decision matrix with each score detailed for each version will be added as an appendix to this report. Here is a table summarizing the final score obtained for each version, as well as the ranking to determine the best solution.

Design version	Final score	Rank	Continue?
Current design	329	3	NO
Version 1	298	10	NO
Version 2	320	5	NO
Version 3.1	309	7	NO
Version 3.2	278	11	NO
Version 4.1	322	4	NO
Version 4.2	309	7	NO
Version 5	256	12	NO
Version 6.1	304	9	NO
Version 6.2	358	2	NO
Version 6.3	313	6	NO
Version 6.4	373	1	YES

Table 7: Details of the final scores obtained for each version, the one highlighted in yellow is the one which will be chosen by the decision matrix

Finally, the decision matrix gives the conclusion that Version 6.4 is the best out of them all overall. Indeed, this design offers many advantages:

- A great strength/weight ratio
- A low number of parts and screws, especially compared to the current version (a connection between four profiles consists of 39 parts in total, screws and bolts included but now it is reduced to 11 with version 6.4)

- A possibility of modularity for different types of connection (which will be studied more in detailed in a future section of this report).

Among the other versions that can be found at the top of the final ranking is version 6.2 which also offers the same advantages but with slightly higher assembly time (because of the higher number of screws) for an overall similar Strength/Weight ratio. The current version can also be found at the top of the ranking, considering its already known advantages, especially about modularity. This proves nonetheless that the current version used by HESS already performs well, which explains why the company have kept that design for more than thirty years. The new 6.4 version does have a few drawbacks that are worth mentioning:

- The geometry of the part is still quite complex. It will then be necessary to carefully choose the material and the manufacturing process to avoid high manufacturing costs.
- This version is not suitable for the current HESS aluminium profiles. Indeed, the profiles used in this version must be threaded so that they can be fixed to the connection parts. This is not the case for the current profiles which are completely hollow.

The last step before going into a detailed analysis of the design is choosing the material, as well as the manufacturing process. Indeed, it has been considered that every part of the assembly was using the same material, but it is also something that must be taken into consideration to optimize the performances of the connection. This must be done before finalizing the design of the parts as this design can vary depending on this choice of material and manufacturing process (some processes only tolerating certain shapes for the parts).

4.5) The choice of the materials and the manufacturing process

4.5.1) The material

The choice of the material can be done by creating a decision matrix just like how it was done for the choice of the design. As previously stated, the most common materials used in the automotive industry are steel, aluminium and CFRP. The objective of this study is to find out in which material the two connection parts will be made. It would be possible to extend the choice of material also to the profiles, but wit will be considered that these profiles will keep the aluminium alloy they currently have to simplify this study which is focused only on the connections for now. The main requirements for a material are summarized in the table 8 below with the associated weight that will be used for the decision matrix (the details of how these weight values have neem obtained will be shown in the appendices).

Requirement n°	Requirement	Unit	Ideal value(s)	Weight (/100)
1	Mechanical properties $\frac{\sqrt{E}}{\rho}$	$GPa^{0.5}m^3kg^{-1}$	Highest	33
2	Thermal properties α	$10^{-6}K^{-1}$	Lowest	7
3	Price	CHF/kg	Lowest	27
4	New material for HESS	Binary	NO	20
5	Possibility of corrosion	Binary	NO	13
6	CO2 footprint	Kg/kg	Lowest	0

Table 8: Summary of all the requirements of the materials, with their way of evaluation and their weight

The values used for comparison will be based on the average properties of a stainless steel, a wrought aluminium alloy like the one that is currently used for the CO-BOLT system, and an epoxy resin infused CFRP. The differences between different types of materials (like different alloys of aluminium) will not be made now as this choice can be greatly influenced by the manufacturing process which will be decided in a next study in this report. The values for all three materials are summarized in the table 9 below.

	Steel	Aluminium	CFRP
Young modulus E (GPa)	210	70	100 (approximately)
Density ρ (kg/m^3)	8000	2700	1600
Coefficient of thermal expansion α ($10^{-6}K^{-1}$)	17	23	1.5
Price ($/kg)	1	2	15
CO2 footprint (kg/kg)	4	12	17

Table 9: Summary of the properties of all the three materials that are being compared in the decision matrix

By using these values, it is possible to give a grade for each material based on the requirements. Here are the results in the table 10 below, for each of the three materials which will determine which one will be used for the rest of this study (as for the previous matrix, all the details are given in the appendices).

Material	Final score	Rank	Continue?
Steel	207	3	NO
Aluminium	253	1	YES
CFRP	227	2	NO

Table 10: Details of the scores obtained by each material, the material highlighted in yellow will be the one chosen by the decision matrix to be used in the rest of this study.

Aluminium will then be chosen material to produce the two connection parts as it is the most versatile of the three materials. Steel is a cheap material, but with a density three times greater than aluminium and five times greater than carbon fibre, it can't be used as a material to make a connection designed originally to reduce the mass of the bus body. Carbon fibre has some excellent mechanical properties but is a lot more expensive than steel and aluminium. Moreover, because this material has never been used for anything to make HESS bus bodies, it can cause challenges for the company, especially to check the regulation like about fire/smoke standards.

4.5.2) The manufacturing process

Now, all that remains to be decided before moving to a detailed analysis is which manufacturing process will be used to produce the parts. This will also help choosing the optimal aluminium alloy afterwards. Once again, the manufacturing process will be chosen thanks to a decision matrix.

Normally, the material and the manufacturing processes should be chosen together in the same decision matrix. However, to make the study easier, two separate decision matrices have been made (the conclusion should still be the same with this method). Here are in the table 11 below the main requirements on which to base the choice of the manufacturing process with the associated weights.

Requirement n°	Requirement	Unit	Ideal value(s)	Weight (/100)
1	Design freedom	Subjective	The fewest limitation on the design	0
2	Tolerance control	mm	Smallest	19
3	Surface finish	Subjective	Low amount of surface irregularities	10
4	Lead time	Days	Lowest	24
5	Tooling cost	CHF	Lowest	5
6	Unit cost	CHF/part	Lowest	29
7	Product strength	E, σ_y	Highest	14

Table 11: Summary of all the requirements of the manufacturing processes, with their way of evaluation and their weight

For all the manufacturing processes, there are unfortunately no precise values that can be found to ensure that they meet each of the requirements. To get the best estimations, it is necessary to directly ask the suppliers. As it wasn't possible to get all the desired values in the time allowed to perform this project, most of them will be judged partially based on a subjective observation. All the manufacturing processes which have been shown in the State-of-the-Art section of the report will be compared. This includes die casting (high pressure die casting, low-pressure die casting, investment casting and sand casting), CNC machining and forging. Here are, on the table below 12, the grades obtained by each manufacturing process.

Manufacturing Process	Final score	Rank	Continue?
High-pressure die casting	252	1	YES
Low-pressure die casting	190	5	NO
Precision casting	200	4	NO
Sand casting	152	6	NO
CNC Machining	252	1	YES
Forging	238	3	NO

Table 12: Details of the scores obtained by each manufacturing process, the manufacturing process(es) highlighted in orange will be the one(s) chosen by the decision matrix to be used for the rest of this study

In this case, after calculating the score for every one of the manufacturing processes, both high-pressure die casting and CNC machining get the highest score. These two processes can be kept in mind for now and a talk with a supplier company, with a detailed analysis of the requirement of the parts will help to choose between the two processes. Forging also got a high score, as it is a common and efficient way to manufacture small aluminium parts (the bracket parts used in the current bus body are made with forging for example). However, the advice from the supplier Prétrat specialised in aluminium parts forging confirmed that the geometry of the parts (especially their small thickness) make it inappropriate for forging, hence the lower grade compared to the other two manufacturing process.

4.6) Detailed design

4.6.1) Design methods in mechanical engineering

In mechanical engineering, numerous methodologies are used to design parts. These methodologies have been developed over the past few decades and ensure to the designed product a low manufacturing cost and a great product reliability. It is a crucial step as it is estimated that over 70% of a product's final cost is determined during the design stage. The most prominent one is called Design for Excellence (DFX). This methodology provides guidelines for all aspects of design and production process. Indeed, it can be separated into different areas for design optimization as seen in the figure 35 below. The two most popular among them all are Design for Manufacture (DFM), Design for Assembly (DFA) and the two combined: Design for Assembly and Manufacture (DFMA). This last methodology will be the focus of this study and what will be used to make the detailed design of the connection parts. [23]

Figure 35: Summary of all the areas relative to the Design for Excellence methodology

Here are the basic principles of DFA and DFM, which must be considered together to make a study about DFMA.

Design for Manufacture:

With DFM, the best design is created with the aim of optimizing the selection of materials and the manufacturing processes, so that it results in the lowest possible cost of production. This implies selecting the best material (here the best aluminium alloy) and the best manufacturing process that goes along with it. It can also include choosing surface treatment methods to also have a product with the best quality. After making such choices, a cost analysis (often with the supplier) must be carried out and if the resulting manufacturing costs are too high, the steps are repeated until reaching an optimal solution.

Design for Assembly:

With DFA, the parts are all designed so that the final product can be easy to assemble. It can be done, for example, by reducing the number of components and the number of assembly operations required. This is essential to optimize the production time and reduce the possibility of assembly mistakes to make more reliable products.

4.6.1) Applications for this project

The application of these two methodologies for the case of this project will now be detailed in this section of the report. For a better understanding, the CAD files of the main parts are added as an appendix to this report.

Modularity:

To begin, one of the first principles of DFA which is already one of the main qualities of the CO-BOLT system is its modularity. Having modular assemblies in a production is one of the best ways to optimize the production of a product. It is especially true for the connections of the CO-BOLT: although all the connections between the profiles are based on the same design, they are all slightly different, especially because of the difference in size and shape of the profiles that are connected. Manufacturing and designing different parts for every one of these connections would be a huge waste of time and money, hence the need to find a modular design which can adapt to these different connections. The solution found to this problem is to add an intermediate piece in the connection between the central parts and the profiles in the way shown in the figure 36 below.
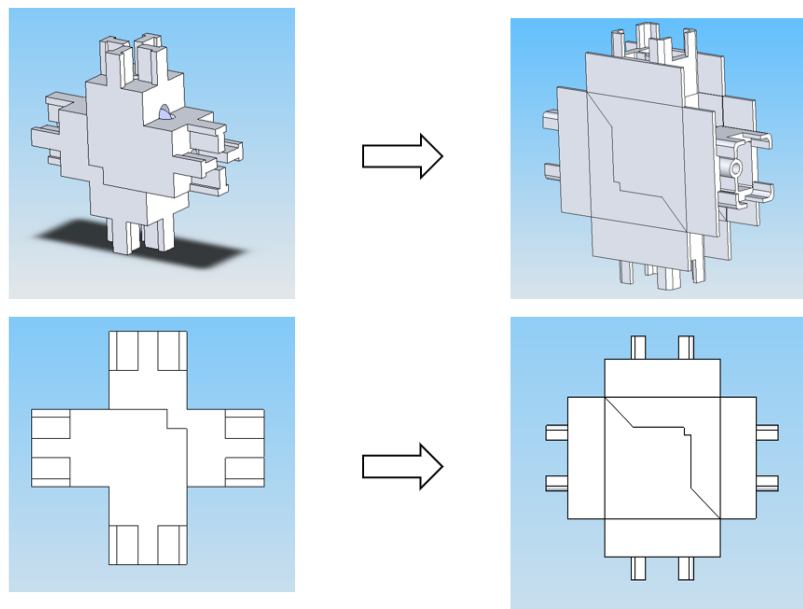
Figure 36: Upgrades made to the connection parts, mainly for modularity purposes

In addition to a few changes made to the design, mainly to make the connection fit the aluminium profiles and for aesthetic purposes, the main upgrade is the integration of a new intermediate piece that fits between the profile and the central connection parts. The two central

connection parts stay the same no matter what the connection type is. However, the intermediate pieces are all unique to every profile they are connected to. The two parts are connected to each other and to the profiles only using a single screw as shown in the figure 37 below.
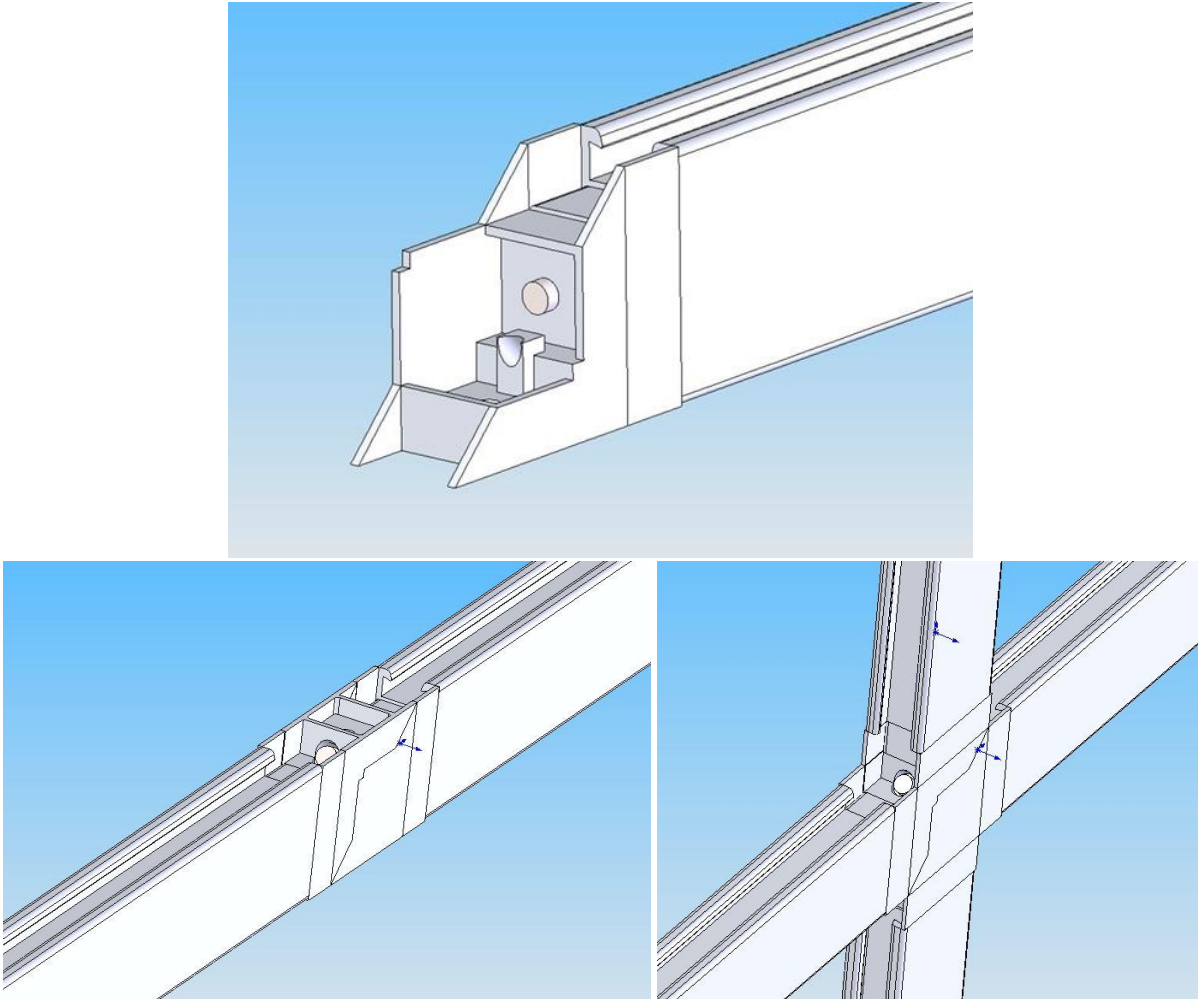
Figure 37: Three pictures of a connection with the new connection parts with respectively one, two and four profiles

Even though this slightly raises the number of parts per connection (for a connection between four profiles, the number of parts raises from 11 to 15, including the screws), this will reduce the number of different parts in the whole assembly and make it simpler both for the production team by avoiding confusion, and for the suppliers, as less different parts must be produced. Here are, in the figure 38 below, a few different cases to explain how this solution can adapt to all the different types of connections.
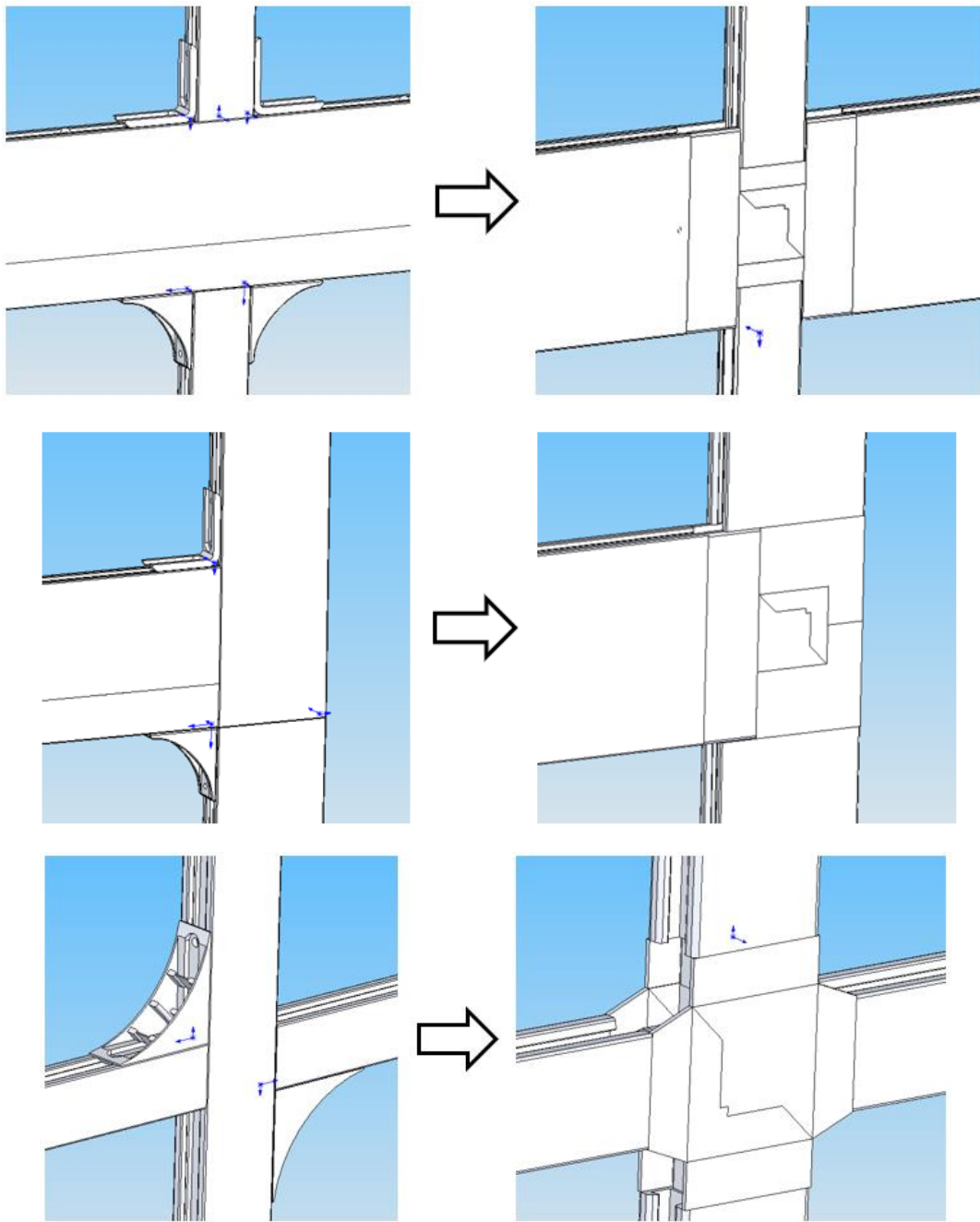
Figure 38: The solution with the new connection parts on the right adapted to three different types of connections currently present on the body that are shown on the left

A solution has also been found in the case of a four-profile connection, where the vertical profiles are not positioned parallel to one another (this is something which is also very present, especially for the side panels). This can be solved by also creating an intermediate part between the two central parts as shown in the figure 39 below.
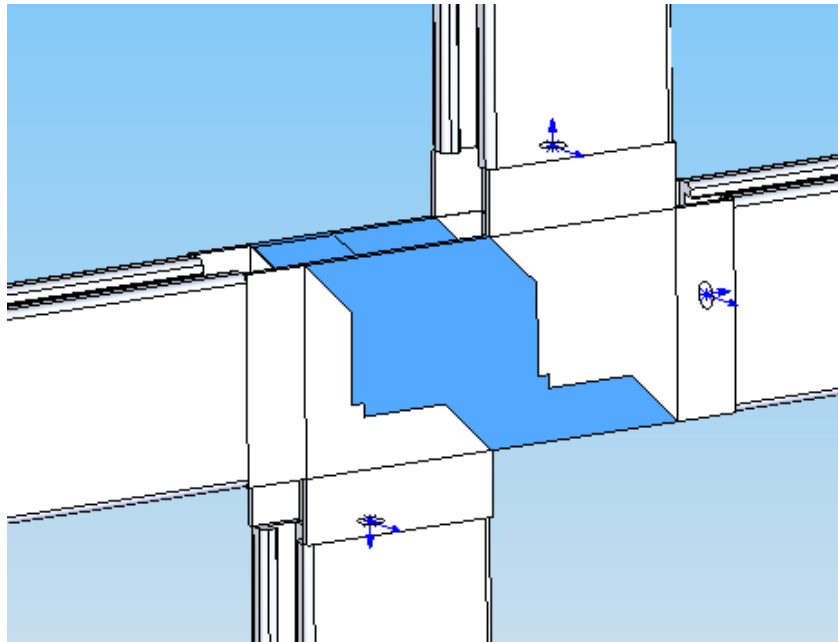
Figure 39: Illustration of how the central connection part can be used to make some specific connections. The additional part that must be added is highlighted in blue

This intermediate part can be made the desired length and doesn't require to manufacture any other parts compared to a same type of connection with parallel profiles positioned with a different alignment. It can also be adapted to different size of profiles especially big ones as seen in the figure 40 below.
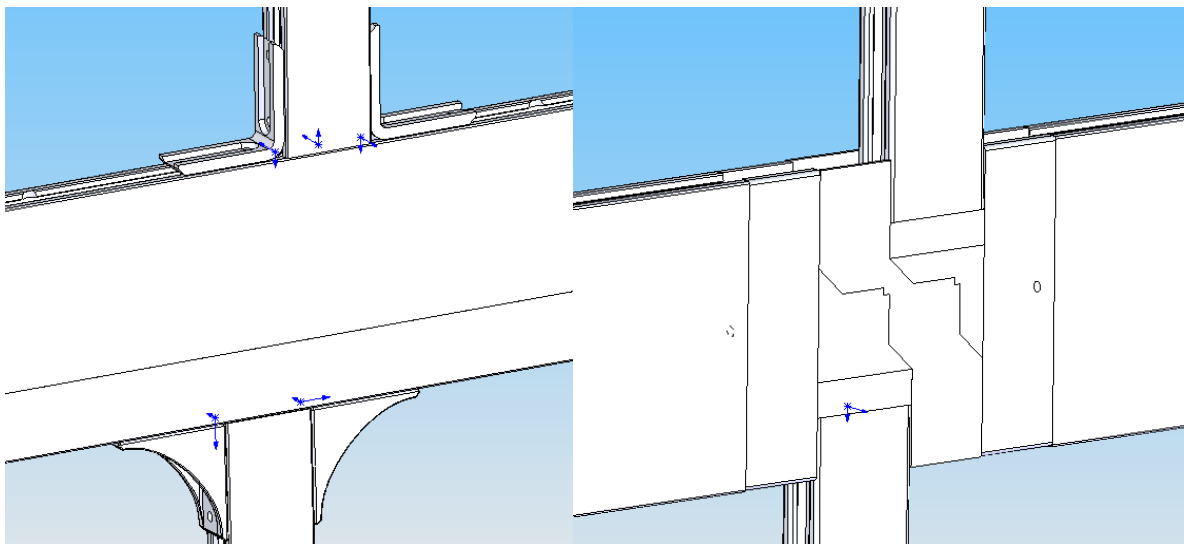
Figure 40: Comparison of a connection with the current model on the left and the new concept on the right

Especially, this type of connection will be really helpful to create the side panels of the bus body, as these connections are very present, as it is possible to see in the figure 41 below, where all the circled areas show where such a design can be used.
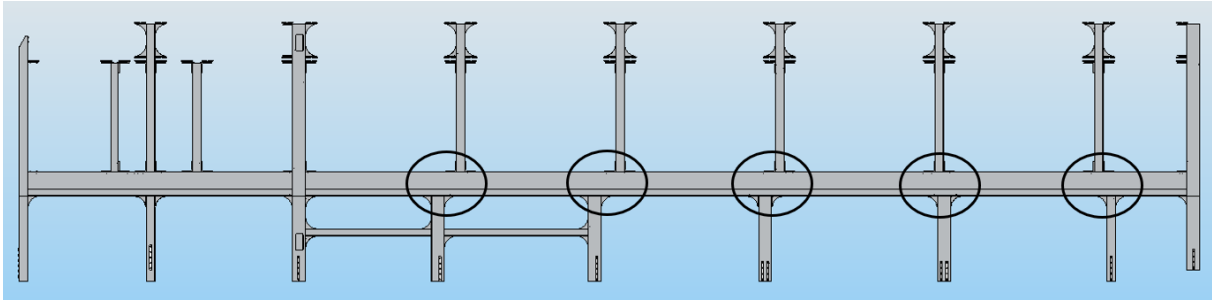
Figure 41: Current side panel locations where the connection shown previously could be used

Symmetry and Mistake proofing:

Another aspect of the DFA methodology is the use of symmetry, or on the other hand anti-symmetry in the design of the parts. Creating a symmetric design can be convenient for the production team as it reduces the time needed by the worker for reorientation. Creating anti-symmetric can also have the advantage of making the part easy to assemble (if the asymmetry is obvious for the worker) but is mostly interesting as it prevents assembling the parts incorrectly. This is one of the basics of the Poka-Yoke principles which aims to minimise potential errors, particularly during assembly. [24]
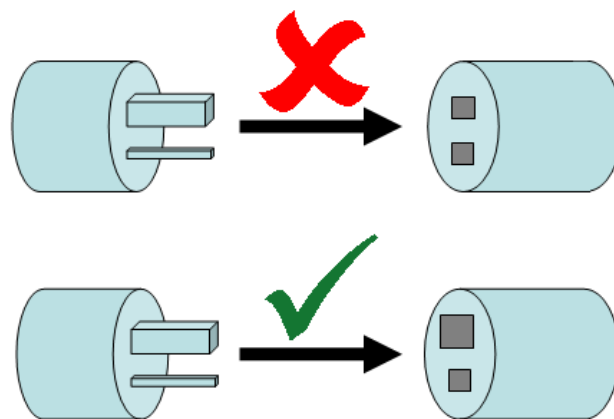
Figure 42: Illustration of the principle of Poka-Yoke, if the two parts are to be assembled in only one possible way, only the second solution can prevent assembly errors.

For example, the intermediate connection part is symmetric about the horizontal axis as there is no difference to the orientation along this axis. However, although it is also symmetrical along the vertical axis, there is only one way it can fit in this direction, but the design of the part ensures that a mistake in the orientation can be immediately seen in an obvious way.
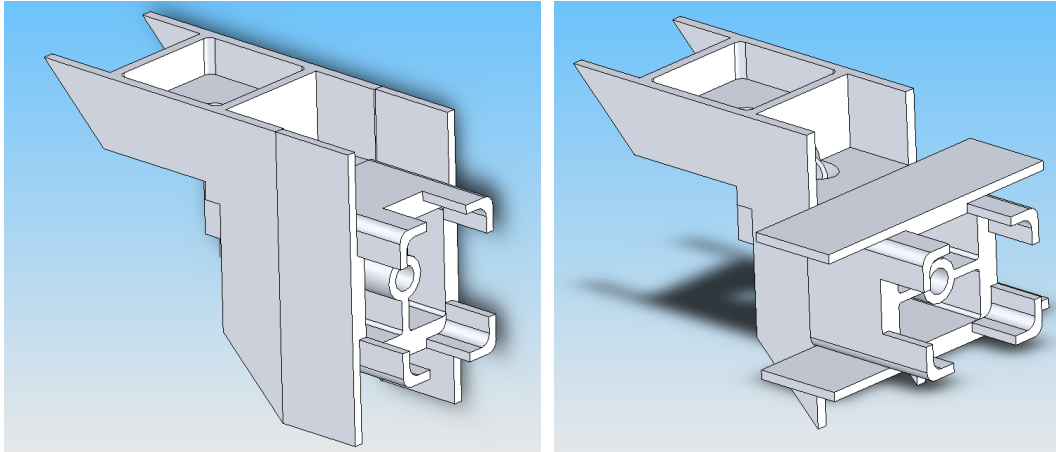
Figure 43: Application of Poka-Yoke for the connection parts with a correct assembly on the left and a wrong assembly on the right

In that case, even though the two assemblies shown in the figure 43 above are technically possible, it is easy to see in the second picture that something is wrong with the sides of the parts not being aligned to each other. Another example of the use of Poka-Yoke in this assembly is with the central part. the anti-symmetric geometry of that part makes it impossible to connect the profiles in the wrong way. Indeed, it can be seen in the figure 34 below that if the yellow profiles are meant to be assembled perpendicularly to the red ones. It is impossible to do the opposite (once all the profiles are fixed to the central part at least) because the geometry of the parts would make them interfere with each other.
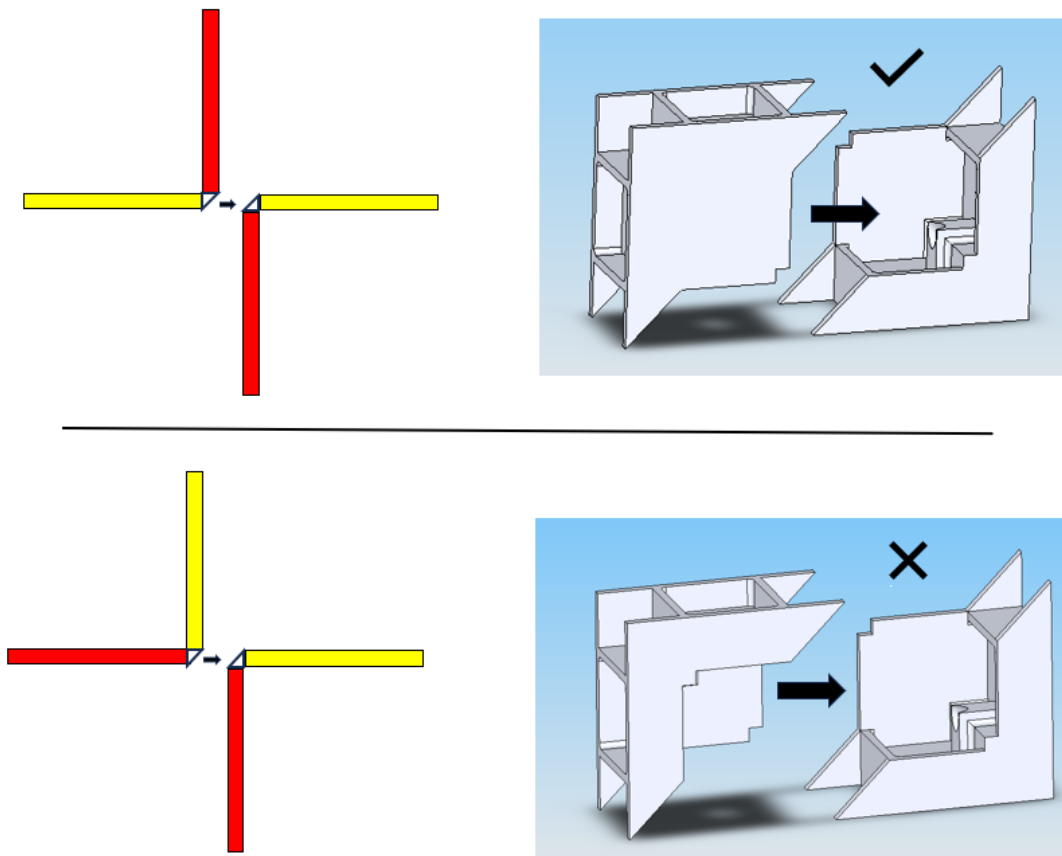
Figure 44: Justification of the geometry of the central connection part for mistake proofing

<u>Manufacturing:</u>

The objective now is to finalize the design of the parts with the aim of minimizing the manufacturing costs of the parts. This is done by applying the methodology of DFM. This part of the design is generally done in cooperation with the suppliers to get some precise estimation of the cost and update the design if it is necessary.

The decision matrix of the manufacturing processes showed that the two most appropriate methods for manufacturing such parts with aluminium are die casting and CNC machining. Two main differences between these two processes will be considered here. The first is the price itself, as die casting is generally cheaper than machining, especially when it comes to producing high quantities of parts. The second is the freedom of choice of the material. This will be an important parameter for the choice of the manufacturing method. These two parameters must be considered together because the purpose of the study is to have a design that is both optimized in terms of strength and weight and cost efficient. Among all the aluminium alloys that can be found in the current market, one commonly used alloy is aluminium 6082. This alloy excels above the rest thanks to its resistance (it is the strongest alloy in the 6xxx series of wrought aluminium) and its high corrosion resistance. This makes it very used when it comes to manufacturing structural components, hence its nickname of "structural aluminium alloy". In addition, its material properties can be enhanced by heat treatment (which makes it classified after that as aluminium 6082-T6). This is a material that HESS is also familiar with, as some of the connector brackets between the profiles are already made with this heat-treated alloy. However, as explained in a previous section of this report, it is not possible to use aluminium 6082 to die cast parts as this alloy is part of the family of wrought alloys. Indeed, with die casting, it is only possible to manufacture parts with certain specific alloys that are called cast alloys. These alloys are generally weaker than the ones from the wrought alloy family. One of the most used cast alloys and one of the ones that also offer the best mechanical properties is aluminium A383 (also called ADC12). Here are, in the table 13 below a comparison of the mechanical properties of both alloys 6082-T6 and ADC12.

	Density (g/cm3)	Yield Strength (Mpa)	Tensile strength (Mpa)	Elongation at break
ADC12	2.74	150	310	3.5%
6082-T6	2.70	**260**	310	**>10%**

Table 13: Summary of the properties of the wrought alloy 6082-T6 and the cast alloy ADC12

In this table, it is possible to see why 6082-T6 would be an ideal material to make the connection parts thanks to its superior mechanical properties. However, because it can only be used to manufacture parts with machining, this may result in higher production costs. An estimation of manufacturing costs with the two processes in comparison to the price of a connection in the current CO-BOLT model will be able to tell if this increase in manufacturing costs is acceptable or not. The price estimation of the manufacturing by die casting was given by the company Get It Made, and the one by CNC machining was given by the company Rp Proto. To make this estimation, a yearly production of 200 buses have been considered, this is how the approximate number of parts to be produced per year are obtained.
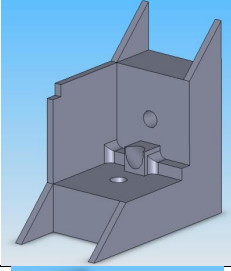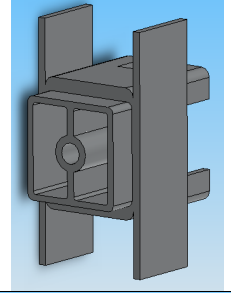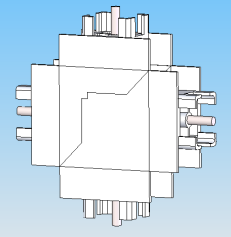
Part	Number of parts produced per year	Price with High-pressure die casting (in CHF)	Price with CNC machining (in CHF)
	25 000	3.5	5.7
	45 000	2.5	2.6
Full connection (between four profiles)	-	**18.5**	**23.3**

Table 14: Comparison of the manufacturing cost of the connection parts with die casting and CNC machining

Based on the estimation given by HESS, a same type of connection would be worth approximately 25 Swiss Francs. So, both the price for machining and die casting are acceptable. That is why machining will be preferred overall because of the better mechanical properties of the used aluminium alloy compared to die-casting. In general, to produce various brackets (as well as doors, connectors, door frames, window frames…), most of them use heat treatable 6000 series aluminum and non-heat treatable 5000 series aluminum. Only engine cylinder and other structurally complex components are produced using the die-casting process and die-casting material. This manufacturing process is then suitable to produce the new connection parts. To make the manufacturing of the connection parts by machining as cheap as possible however, it was necessary to optimize the geometry of the part, especially to reduce the waste of material. This is especially an issue for the central part (the geometry of the intermediate part is already suitable for machining, hence the very low-price difference of price between the two processes). Therefore, two upgrades have been made to this part. These upgrades are shown in the figure below. Version 2 is a necessary upgrade to do on all the parts as otherwise, the sharp angles will make it impossible to manufacture, whatever the manufacturing methods will be. Version 3 limits the number of holes, which makes it simpler to make with the tools used in aluminium machining. This update, however, makes the part slightly heavier than the two previous version but the price will be greatly reduced which can make it better to use by HESS for future uses. It is also important to precise that a surface treatment will have to be applied following the manufacture of these parts to avoid corrosion in case they come into contact with water for example.
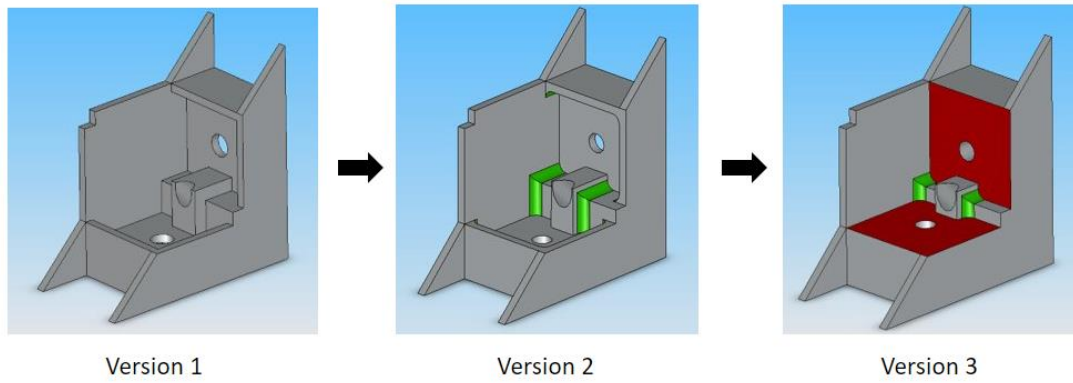
Figure 45: Changes made to the central connection part to make it easier and cheaper to manufacture

4.7) Design of the profile

Now that the connections for the bus body are fully designed, one last detail to take into consideration for the design of the whole bus body is the design of the aluminum profiles. Indeed, as mentioned previously, the profiles of the CO-BOLT will have to be slightly changed to add a thread at the center of the profiles so that they can be screwed to the connection parts. However, to avoid losing strength in the bus body, the profiles must have at least the same strength as the current ones, while keeping the area of the cross section (and thus the weight of the profiles) as small as possible. As explained previously in this report, the strength of the profiles is determined by the values of the moments of inertia Ix and Iy, as well as the torsional stiffness K of the cross section of the profiles. The objective is that these values for the new profiles don't exceed the ones of the current profiles. Here is, in the figure 46 below, one design that have been found for one of the profiles (the most basic and the most used in the whole bus body) and its comparison to the current one. The thickness have been slightly reduced on the sides to make it possible to have an area to be threaded on the center without generating an excessive increase in the cross-sectional area. The comparison of the properties of the two profiles is given in the table 15 below.
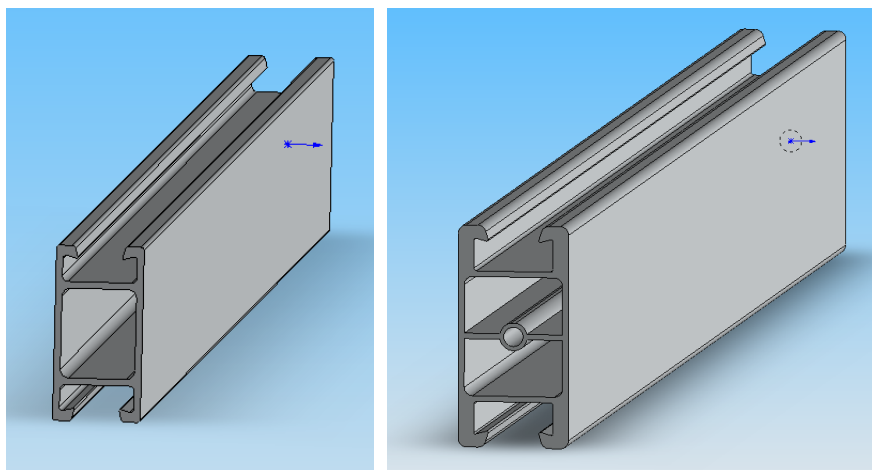
Figure 46: Comparison of the current profiles of the body on the left and the new concept to adapt to the new parts on the right

	Current profile	New profile	Difference
Area (cm^2)	8.25	8.55	**+ 3.6 %**
Ix (cm^4)	21.27	22.09	+ 3,9 %
Iy (cm^4)	53.33	61.23	+ 14,8 %
Polar moment of inertia (cm^4)	74.6	83.32	+ 11,7 %

Table 15: Comparison of the mechanical properties of the current profiles and the new ones

Therefore, even though the area of the cross section had to be increased, the profiles are still as strong as the current ones, while being able to be fixed thanks to the thread at the center. A more precise optimization could probably make the profile lighter with similar strength but that is not the focus of this study. It is also possible to do the same for every type of profile. In the end, the weight gained because of the increased area of the cross section of the profiles should be compensated by the weight saved in the connections. For later price estimations, it will be considered that the price is approximately the same in the two versions (CHF 100 per meter on average) considering that the two versions have similar geometries and similar cross-section areas. Another important aspect in the design of the profiles is that the overall dimensions (here for the profile above: 40mm x 80mm) are the same for the new profiles. The external geometry has not been modified too much to make the profiles adaptable for a potential use in the current CO-BOLT model. Indeed, it is still possible to use the current bracket connection type with these new profiles, which makes it possible to assemble a connection with both a profile from the original CO-BOLT system and from the new one.
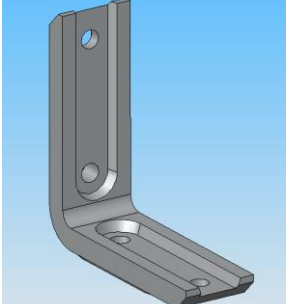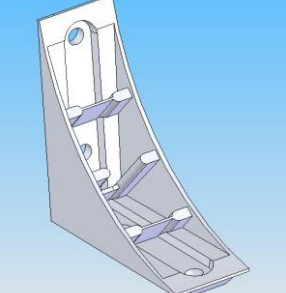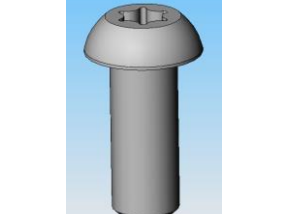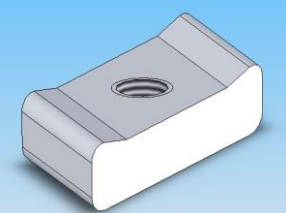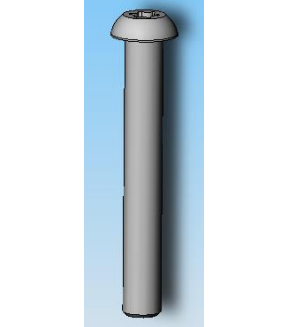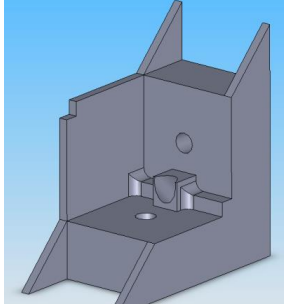
5) Results

Now that all the parts of the new CO-BOLT 2.0 model have been designed, the influence of these new connections can be checked for the whole bus body, to ensure that this new concept meets the requirements of the project. As a reminder, here are the main requirements of the new bus body, stated in the guidelines of the thesis itself:

-Reduced assembly time

-Reduced weight

-Reduced number of parts

-Increased strength and stiffness

-Lower Price (this requirement is not stated in the guidelines of the project, but it is still an essential parameter to evaluate for the company).

5.1) Evaluation of the Weight, the price, and the number of parts of the CO-BOLT 2.0

Firstly, the weight, the price, and the number of parts are easy parameters to evaluate. The weight and the price can be measured for every component and then added up to obtain a value for the weight and the price of the whole system for both the current CO-BOLT model and the CO-BOLT 2.0. To simplify this study, it will be considered that all the profiles have the same cross-section, and that the connections are the same everywhere. Here is the summary, in the table 16 below, of the weight and the prices of these parts. The price for the already existing parts has been given by HESS and the price for the new connection parts has been given by suppliers, by considering a production of these parts with CNC machining.

Part	Weight (kg)	Price (CHF)	Use
	0.15	3.25	CO-BOLT 1.0
	0.20	3.75	CO-BOLT 1.0 + CO-BOLT 2.0
	0.02	0.2	CO-BOLT 1.0
	0.02	0.1	CO-BOLT 1.0
	0.03	0.3	CO-BOLT 2.0
	0.10	5.7	CO-BOLT 2.0
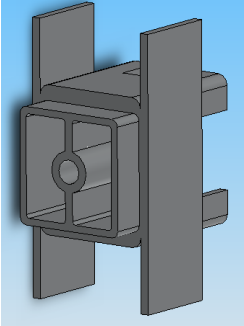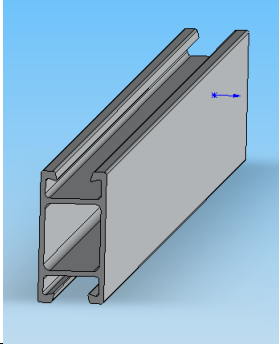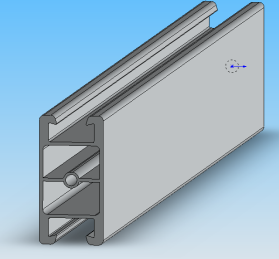
	0.09	2.6	CO-BOLT 2.0
	2.23 (for 1m)	100 (for 1m)	CO-BOLT 1.0
	2.30 (for 1m)	100 (for 1m)	CO-BOLT 2.0

Table 16: Evaluation of the weight and the cost of all the parts from both the current bus body and the new one

The new connection parts will be implemented on the body as shown in the figure 47 below, representing a simplified version of the bus body for a 2-axle model. The blue and black parts all represent an assembly of parts that is used to make the connection. All these assemblies can now get their prices and their weight estimated in the table 17 below. Some current connection parts will still be kept to make some connections on the roof of the bus body. That is because these connections require just the use of one bracket part, and it is therefore not profitable to change that connection as it would only make it more complex and expensive. The connections between the side panels and the roof to the big profiles that connect the three main assemblies of the bus bodies (the ones with a dotted line on the figure below) have also remained unchanged because the complex geometry of these profiles would make it complicated to adapt the new connection methods with these profiles.
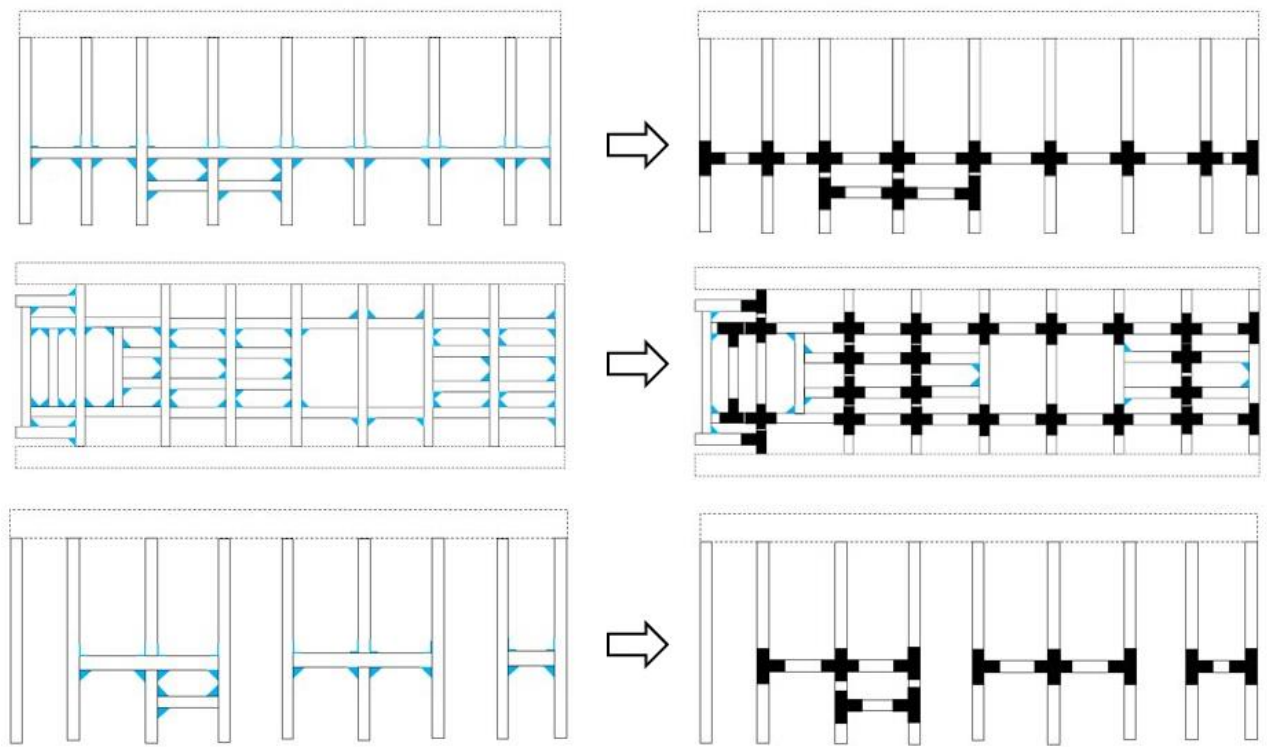
Figure 47: Illustration of how and where the old bracket connection parts were replaced by the new connection parts
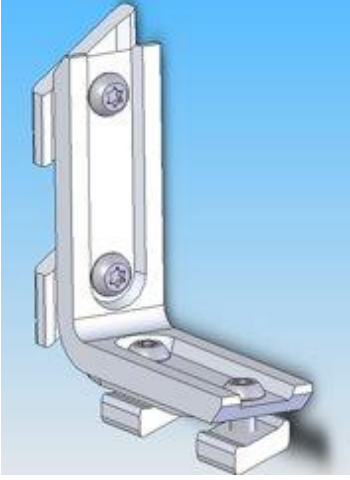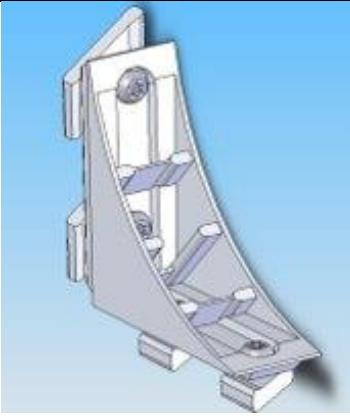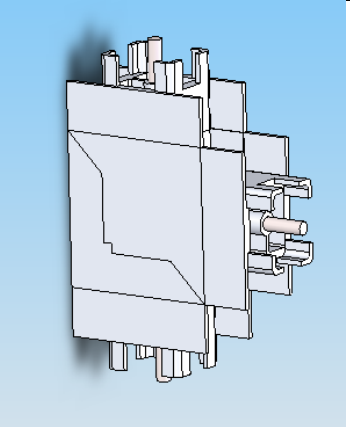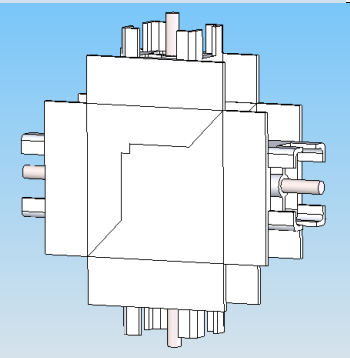
Symbol from fig 46	Part	Weight (kg)	Price (CHF)	Number of parts
		0.31	5.2	9
		0.36	6.2	9
		0.59	20.4	9
		0.71	23.3	11

Table 17: Comparison of the weight, the price, and the number of parts of different connection assemblies

Now, it is possible to estimate the price and the weight for each CO-BOLT version after estimating the values in the tables 18 and 19 below for the two CO-BOLT models.

CO-BOLT 1.0:

	Total length of aluminium profiles (mm)	Total number of profiles	Total number of ∟ assemblies	Total number of ◣ assemblies
2-Axle	120 000	75	26	101
3-Axle	155 000	100	38	132
4-Axle	200 000	125	46	170

Table 18: Number of profiles and connection parts for each type of bus (using the CO-BOLT 1.0)

CO-BOLT 2.0:

	Total length of aluminium profiles (mm)	Total number of profiles	Total number of ⊢ assemblies	Total number of ✚ assemblies	Total number of ◣ assemblies
2-Axle	110 000	115	18	30	14
3-Axle	144 000	150	29	36	14
4-Axle	186 000	185	37	45	22

Table 19: Number of profiles and connection parts for each type of bus (using the CO-BOLT 2.0)

Here is, in the end and in the table 20 below, the full comparison of the weight, the price and the number of parts for both the CO-BOLT 1.0 and the CO-BOLT 2.0 using the new connection parts. Because all the values are not perfectly accurate and are based on approximations, it can be said that the values have a margin of error of +/- 10 %.

		WEIGHT (kg)	PRICE (CHF)	NUMBER OF PARTS
2-Axle	CO-BOLT 1.0	312	12 700	1218
	CO-BOLT 2.0	291	12 100	733
	Difference	**-21 kg**	**-600 CHF**	**-485 parts**
3-Axle	CO-BOLT 1.0	405	16 400	1630
	CO-BOLT 2.0	380	15 900	933
	Difference	**-25 kg**	**-500 CHF**	**-697 parts**
4-Axle	CO-BOLT 1.0	521	21 200	2069
	CO-BOLT 2.0	491	20 500	1211
	Difference	**-30 kg**	**-700 CHF**	**-858 parts**

Table 20: Summary of the difference in the weight, the price, and the number of parts for the CO-BOLT 1.0 compared to the CO-BOLT 2.0

In conclusion, the weight, the price, and the number of parts have all been slightly reduced. The requirements in relation to these parameters are thus respected. Two requirements have yet to be validated. These are the strength of the bus and the manufacturing time.

5.2) Evaluation of the strength of the CO-BOLT 2.0

There are multiples way to evaluate the strength of an assembly. As there are no precise requirements about how the strength of the bus body should be measured. The evaluation of this requirement can be done by comparing a FEA analysis of both the CO-BOLT 1.0 and the CO-BOLT 2.0, and especially by comparing the location of the stresses, the maximum value of stress and the maximum value of displacement. However, as it was explained previously in this report, it is difficult and time consuming to do a precise FEA simulation for the whole bus body. It can be possible however, to do a simple simulation for the case of just a single connection. This simulation will not provide the most accurate results but can still give an idea about the behavior of the new bus body when it is subjected to some specific loads. The simulation will be done under the same condition as the simulation that was used to test the strength of the different connections to complete the decision matrix in a previous part of the report, with three of the four profiles being fixed on their ends and the last remaining profile being subjected to a three-dimensional load, representative of the forces applied to the profiles of the side panels because of the weight on the roof. The results of the simulation are shown in the figure 48 below.
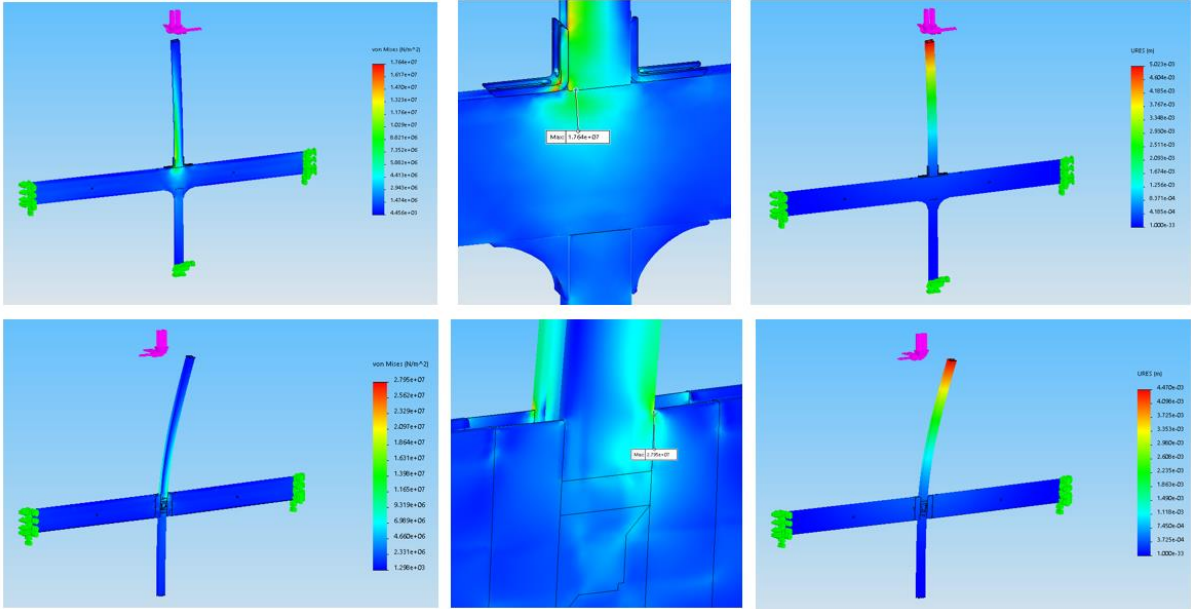

Figure 48: Illustration of the FEA simulation done with the current connection on the top and the new one on the bottom. the pictures on the left show the results for the stresses, with a zoom to the maximum location on the middle, and the displacements are shown on the right

The first thing that can be analyzed is the comparison of the maximum value of the stresses between the two profiles. The maximum von mises stress is 17.6 N/mm2 for the CO-BOLT 1.0 whereas this value rises to 28.0 N/mm2 for the new CO-BOLT 2.0. The stresses are also much more concentrated

on a single point for the new model than for the current model where the stresses are more evenly distributed over the contact area between the bracket parts and the profiles. The new design is therefore not optimal for the distribution of the stresses in the connection. However, there is still room for improvement to optimize the design of the connection parts, especially for the intermediate connection parts in which the design has been made exclusively to make the assembly simple, modular, and aesthetically pleasing. The strength of this part has not really been taken into consideration for its design. It could then be possible to improve the design for better results regarding the strength of the connection. However, if the displacements are observed, it can be noticed that the maximum value of displacement for the CO-BOLT 1.0 model (5.0mm) is slightly higher than the one for the CO-BOLT 2.0 (4.5mm). If the evaluation of the strength of the bus is based on a displacement criterion, it is still fair to stay that some improvements were made regarding the strength of the bus body when using the CO-BOLT 2.0. This requirement is therefore partially met.

5.3) Evaluation of the manufacturing time of the CO-BOLT 2.0

About the assembly time, it is impossible to get a precise evaluation of this parameter and thus a comparison between the two bus models without making real prototypes of the parts. However, because the number of parts has been reduced in the assembly (especially the number of screws), it is also fair to say that the assembly time will be reduced as well when using the new CO-BOLT 2.0 model. The time saved will be greater the more parts are saved, which is particularly the case for large 3-axle and 4-axle buses. It is possible to get an estimation of the time taken to put all the screws in place in the assembly, if it is considered that it takes an average time of ten seconds to put one screw.

		NUMBER OF SCREWS	TOTAL SCREWING TIME
2-Axle	CO-BOLT 1.0	508	1h 25min
	CO-BOLT 2.0	278	45min
	Difference	**-230 screws**	**-40min**
3-Axle	CO-BOLT 1.0	680	1h 55min
	CO-BOLT 2.0	352	1h
	Difference	**-328 screws**	**-55min**
4-Axle	CO-BOLT 1.0	864	2h 25min
	CO-BOLT 2.0	461	1h 15min
	Difference	**-403 screws**	**-1h 10min**

Table 21: Summary of the potential reduction of assembly time

Therefore, when looking at the results shown in the table 21 above, it is obvious that the screwing time have been greatly reduced with the new design of the CO-BOLT 2.0. The screwing time is only part of the total assembly time, and therefore cannot by itself prove that the buses will be assembled faster, but it does reveal some of the progress that this will bring to the assembly.

5.4) Final verdict

In conclusion, it can be said that the solution meets most of the requirements. Here is a summary based on the results of the previous parts in the table 22 below.

Requirements	2-axle bus	3-axle bus	4-axle bus
Reduced assembly time	**YES, TO BE CONFIRMED** (At least 40min less of screwing time)	**YES, TO BE CONFIRMED** (At least 55min less of screwing time)	**YES, TO BE CONFIRMED** (At least 1h 10min less of screwing time)
Reduced weight	**YES** (21 kg less approximately)	**YES** (25 kg less approximately)	**YES** (30 kg less approximately)
Reduced number of parts	**YES** (485 parts less, screws and nuts included)	**YES** (697 parts less, screws and nuts included)	**YES** (858 parts less, screws and nuts included)
Increased strength and stiffness	**PROBABLY** (Would need further analysis and a more optimized design, the values of the maximum displacements have still been reduced nonetheless)		
Lower Price (optional)	**YES** (600 Francs cheaper approximately)	**YES** (500 Francs cheaper approximately)	**YES** 700 Francs cheaper approximately)

Table 22: Summary of the advantages of the CO-BOLT 2.0

The conclusion can be drawn that all three types of buses could potentially use the CO-BOLT 2.0 for the body. However, to be sure of this, it would be necessary to move on to the next stage in the design process and produce prototypes to be sure about the performances of the new body model. This report will not focus on this part of the design process though.

6) Conclusion

Finally, this project led to the creation of the CO-BOLT 2.0, a new model of bus body, which is an improvement on the previous CO-BOLT 1.0 body model made by HESS, especially thanks to the implementation of new connecting parts. These connection parts are made in aluminium, just like the rest of the assembly of the body and CNC machining is used to manufacture these parts. Based on the results, the conclusion can be made that using the new bus model would reduce the weight of the vehicle, as well as the assembly time while being cost-efficient if it were to be used by HESS. The economy in the weight of the bus would enable its users to save energy, thus making HESS buses even more attractive for potential customers. The time saved in the assembly of the buses would make it easier for HESS to ensure that delivery times are respected and for the production team as well, because the body would be made easier to assemble. The effect on the strength of the bus is still questionable however, as different conclusions are given when analyzing the effect according to different criteria. This could nonetheless be improved with further research on the design of the body, especially on the connection parts. In addition, there are still some areas for improvement in this project that could be studied in greater depth.

7) Future Work

To fully complete this project and to make this new bus body work for HESS, some additional work would have to be done. This last section of the report describes some possible future work that would be necessary to do to implement the CO-BOLT 2.0 model into HESS's buses.

As mentioned in the previous sections of the report, it would be necessary to focus a bit more on the design of the connection parts with the aim of optimizing the strength of the body. This would probably require some advance knowledge in the modelling of materials and take a lot of time, that is why it was not studied in detail for this project. The methods used to check the strength of the structure could also be improved. Indeed, it would be much better to represent the full bus body on a powerful FEA software to get the most precise estimations for the values of the stresses and the displacement. Another criterion that could have been used to estimate the strength of the bus body is a modal criterion by performing a vibration analysis and estimating the natural frequencies of the structure. The higher these frequencies would be (and the furthest away are these values from the natural frequencies of the road), the stronger the whole assembly would be.

Research could also have been undertaken to improve the body in another way. For example, by optimizing the layout of the body (the location of the aluminium profiles). However, the whole bus assembly would have to be studied, and not only the assembly of the body itself, as there the profiles are often positioned to make the rest of the assembly (like the chassis or the interior of the bus) possible. The use of carbon fibres would perhaps have deserved a little more attention in this project, given that despite the drawbacks that have been mentioned, it remains a material that is increasingly used in the automotive industry and could be the solution to most of the vehicle's issues about strength and weight if research into composite materials goes on.

References

[1]. Home—Hess AG https://www.hess-ag.ch/

[2]. Home – Nova Bus Accueil - Novabus

[3]. Home – Ebusco Ebusco® - Made to move people

[4]. ANDERTON, James. Advantages of Adhesive Bonding for Composite Materials. 22 February 2018

    Advantages of Adhesive Bonding for Composite Materials | Engineering.com

[5]. ASHBY, Michael. Materials Selection in Mechanical Design Third Edition. July 2004 Materials

    selection textbook.pdf (idu.ac.id)

[6]. Galvanic Corrosion – Carbon Fiber and Aluminum—Composite Envisions. 2002 Galvanic Corrosion

    – Carbon Fiber and Aluminum - Composite Envisions

[7]. Aluminum and Aluminum Alloys Screen_Art-5a.pdf (nist.gov)

[8]. Yi, W.; Liu G.; Gao J.; Zhang L. Boosting for concept design of casting aluminum alloys driven by

    combining computational thermodynamics and machine learning techniques. J. Mater. Inf. 30

    December 2021. https://jmijournal.com/article/view/4487

[9]. Quelles sont les différentes façons de fabriquer des pièces en aluminium ? - Service d'usinage

    CNC, Prototypage rapide. *CNC Machining Service, Rapid prototyping*. Pro-Lean. 7 February

    2023 https://proleantech.com/fr/what-are-the-different-ways-to-make-aluminum-parts/

[10]. Aluminum Extrusion 101: A Comprehensive Guide To Its Process. WayKen Rapid Manufacturing.

    4 November 2022 Aluminum Extrusion 101: A Comprehensive Guide to Its Process - WayKen

    (waykenrm.com)

[11]. CNC Machined vs Forged. High Level manufacturing for very different needs. *Greg Sewell

    Forgings*. 2021. https://gsforgings.com/blog/forging-vs-machining/

[12]. Costo de fundición a presión: cómo calcular el costo de fundición a presión. Rapid Direct. 2 April

    2022. Costo de fundición a presión: cómo calcular el costo de fundición a presión -

    rapiddirect

[13]. High Pressure vs Low Pressure Aluminum Die Casting. Sunrise. 2023 High Pressure Aluminum Die Casting - Aluminum Pressure Die Casting (sunrise-metal.com)

[14]. Leading Aluminum Forging Companies Aluminum Forging Companies | Aluminum Forging Services

[15]. NORDIN David. Design and Evaluation of a Carbon Fibre Bus Body. 2018 FULLTEXT01.pdf (diva-portal.org)

[16]. Adhesive Bonding vs. Mechanical Fastening in Product Design: The Pros and Con. Brighton Science. February 2023 Adhesive Bonding vs Mechanical Fastening in Product Design (brighton-science.com)

[17]. Which Aluminum Alloys are Best for Welding, and Can You Weld Your Product? by Gabrian Team | Gabrian Blog, Aluminum Alloys Which Aluminum Alloys are Best for Welding? - Gabrian

[18]. How to join aluminium profiles, Tuli - Jure Pleško. 24 March 2023 How to join aluminium profiles - Tuli experience (tuli-shop.com)

[19]. Aluminum Framing Extrusions & Aluminum Tubing Connectors. Eagle Aluminum Aluminum Tubing Connectors, Fittings, & Framing Extrusions (eagle-aluminum.com)

[20]. 20 Aluminum Profile Connection Modes for Non-Standard Equipment. Shane. 19 July 2023 20 20 Aluminum Profile Connection Modes for Non-Standard Equipment | MachineMfg

[21]. M8 Extrusion tap. GAP Engineering PTY LTD M8 Extrusion tap - GAP Engineering

[22]. Static Failure Mode Prediction Models Mechanically Fastened Joints Joining & Assembly. TU Delft 714c - Failure Mode Equations (tudelft.nl)

[23]. Velling A. Design for X (DFX) Methods. 17 June 2021 Design for X (DFX) | 10 Approaches of DFX Explained | Fractory

[24]. Poka-Yoke (groupe mardi), methodesqualite, 2010 Poka-Yoke (groupe mardi) | Les méthodes d'amélioration de la qualité (wordpress.com)

Table of figures

Appendices

A: Gantt Chart

Milestones	Weeks 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Vacation 19	20	21	22
Introduction	■																					
State of the art	■																					
Observation of the assembly of the CO-BOLT with the production team						■	■															
Conclusion about the possible improvements of the CO-BOLT							■															
Design of the new possible concepts											■	■										
Decision matrix to choose the right design													■	■								
Analysis of the materials and the manufacturing processes															■	■						
Detailed design																	■	■				
Results																	■	■			■	
Report writing	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■

B: Decision matrices

Choice of the solution:

HESS

Wertschöpfungsprozess

W3-FO-018

Block 1

Requirements	Weight	V0 Note	V0 Points	V0 Product	V1 Notiz	V1 Punkte	V1 Produkt	V2 Notiz	V2 Punkte	V2 Produkt	V3.1 Notiz	V3.1 Punkte	V3.1 Produkt	V3.2 Notiz	V3.2 Punkte	V3.2 Produkt	V4.1 Notiz	V4.1 Punkte	V4.1 Produkt
1 Strength/Weight ratio	18	0	4	71	338	0	0	109	2	36	113	3	53	113	3	53	102	4	71
2 Assembly time	16	8	1	16	6	3	47	6	3	47	G	0	0	8	1	16		0	0
3 Assembly complexity	9		2	18		2	18		2	18		4	36		3	27		4	36
4 Part complexity	11		4	44		4	44		5	56		4	44		3	33		4	44
5 Modularity	4		5	22		5	22		1	4		1	4		1	4		0	0
6 Number of parts	13	23	1	13	11	3	40	16	2	27	5	5	67	21	1	13	5	5	67
7 Repairability	7		5	33		4	27		5	33		0	0		4	27		2	13
8 Adaptability with Co-Bolt 1.0	2		5	11		0	0		0	0		2	4		2	4		2	4
9 Aesthetics	0		5	0		5	0		5	0		2	4		2	4		5	0
10 Compliance with ECE regulations	20		5	100		5	100		5	100		5	100		5	100		5	100
Sum				**329**			**298**			**320**			**309**			**278**			**322**
Rang				**4**			**11**			**6**			**8**			**12**			**5**

Block 2

Requirements	Weight	V4.2 Notiz	V4.2 Punkte	V4.2 Produkt	V5 Notiz	V5 Punkte	V5 Produkt	V6.1 Notiz	V6.1 Punkte	V6.1 Produkt	V6.2 Notiz	V6.2 Punkte	V6.2 Produkt	V6.3 Notiz	V6.3 Punkte	V6.3 Produkt	V6.4 Notiz	V6.4 Punkte	V6.4 Produkt
1 Strength/Weight ratio	18	102	4	71	126	2	36	97	5	89	97	5	89	97	5	89	97	5	89
2 Assembly time	16	8	1	16	8	1	16	0	0	0		3	47		1	16		4	62
3 Assembly complexity	9		2	18		3	27		3	27		3	27		3	27		4	36
4 Part complexity	11		3	33		3	33		2	22		2	22		2	22		2	22
5 Modularity	4		0	0		0	0		3	13		3	13		3	13		3	13
6 Number of parts	13	13	3	40	21	1	13	10	4	53	12	3	40	14	3	40	11	3	40
7 Repairability	7		4	27		4	27		3	20		3	20		1	7		3	20
8 Adaptability with Co-Bolt 1.0	2		2	4		0	0		0	0		0	0		0	0		0	0
9 Aesthetics	0		2	4		0	0		0	0		0	0		0	0		0	0
10 Compliance with ECE regulations	20		5	100		5	100		5	100		5	100		5	100		5	100
Sum				**309**			**256**			**304**			**358**			**313**			**373**
Rang				**8**			**13**			**10**			**3**			**7**			**1**

Choice of the material:

HESS

Material Selection Matrix

Requirements	Weight / Note	Steel Points	Steel Product	Aluminum Punkte	Aluminum Produkt	CFRP Punkte	CFRP Produkt
1 Strength/weight ratio	33	1	33	3	100	5	167
2 Thermal properties	7	3	20	2	13	1	33
3 Price	27	5	133	4	107	1	27
4 Regulations	20	1	20	1	20	1	0
5 Corrosion	13	0	0	1	13	0	0
6 CO2 footprint	0	5	0	2	0	3	0
			207		253		227
			Rang 3		Rang 1		Rang 2

Legend:
- WICHTIG
- Calculated fields
- Cell references

Wertschöpfungsprozess

No. Vertical	Requirements	Strength/weight ratio	Thermal properties	Price	Regulations	Corrosion	CO2 footprint
1	Strength/weight ratio						
2	Thermal properties	1					
3	Price	1	3				
4	Regulations	1	4	3			
5	Corrosion	1	5	3	4		
6	CO2 footprint	1	2	3	4	5	

Choice of the manufacturing process:

HESS — Wertschöpfungsprozess — W3-FO-018

Legend: WICHTIG · berechnete Felder · Zellbezüge

Ziele / Kriterien	Gewicht	Precision casting (Punkte / Produkt)		Sand casting (Punkte / Produkt)		Forging (Punkte / Produkt)		High-pressure die casting (Punkte / Produkt)		Low-pressure die casting (Punkte / Produkt)		CNC Machining (Punkte / Produkt)	
1 Design freedom	0	3	0	2	0	1	0	3	0	1	0	3	0
2 Tolerance control	19	3	57	1	19	2	38	3	57	1	19	3	57
3 Surface finish	10	3	29	1	10	2	19	3	29	2	19	3	29
4 Lead time	24	2	48	2	48	2	48	2	48	2	48	3	71
5 Tooling cost	5	2	10	1	5	1	5	1	5	1	5	2	10
6 Unit cost	29	1	29	2	57	3	86	3	86	3	86	2	57
7 Product strength	14	2	29	1	14	3	43	2	29	1	14	2	29

	Precision casting	Sand casting	Forging	High-pressure die casting	Low-pressure die casting	CNC Machining
Summe	200	152	238	252	190	252
Rang	4	6	3	1	5	1

Pairwise comparison (Ziele)

Nr. Vertikal / Nr. Horizontal	Design freedom (1)	Tolerance control (2)	Surface finish (3)	Lead time (4)	Tooling cost (5)	Unit cost (6)	Product strength (7)
1 Design freedom							
2 Tolerance control	2						
3 Surface finish	3	2					
4 Lead time	4	4	4				
5 Tooling cost	5	2	3	4			
6 Unit cost	6	6	6	6	6		
7 Product strength	7	2	7	4	7	6	

The CAD files of the most important parts, and those which are not confidential, will be given as an attachment to this report.

Here are the 3D STEP files of the parts that can be found attached to this report:

-Central.STEP

-Int.STEP