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Faculty of Mechanical Engineering, Informatics and
Electrical Engineering
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Thesis

Wheel center design of a Formula Student race car

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Vehicle technology**

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Task assignment form

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Tasks in detail:

1. Literature research:
 - o rim designs
 - o machining technology
 - o additive manufacturing technology
 - o unsprung and rotating mass effects
 - o competitor analysis
2. Design:
 - o Determination of the acting forces
 - o machined and printed pro/con
 - o machined center design
 - o generative design
 - o comparison (physical characteristics, manufacturability, cost)
3. Summary/conclusion

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Student's Declaration

I, the undersigned Dániel Bársony (IXOGXL), Mechanical Engineering BSc, hereby declare that "Wheel center design of a Formula Student racecar" is my own work where I only used the given references to the given extent in compliance with the rules of citation by accurately providing the references.

My results are based on my own work, calculations, research, real measurements and according to the best of my knowledge they are authentic.

25.11.2022.

date

Dániel Bársony

Student's signature

Kivonat

A hallgató neve:	Bársony Dániel
A diplomamunka címe:	Formula Student versenyautó felni centerének tervezése
Külső konzulens:	-
Belső konzulens:	Kaszab Martin, kutatómérnök

Szakdolgozatom célja a győri Széchenyi István Egyetem hallgatói versenycsapataként működő Arrabona Racing Team tizedik Formula Student versenyautójának felni centerének megtervezése.

Ahhoz, hogy a tervezést a lehető legmegfelelőbben elvégezzem, irodalomkutatást végeztem felnik és kerekek tervezésére, valamint az ezekhez kapcsolódó gyártástechnológiák témájában. Ezután versenytárs elemzést végeztem, amely segítségével bemutatom a Formula Studentben elterjedt felni és center kialakításokat. Majd bemutattam és megvizsgáltam a csapat által korábban használt kerék és center változatokat.

Először vázoltam a követelményeket és kritériumokat, amelyek a centereknek meg kell felelniük, és fő céljuk a minimális tömeg, a biztonságos működés és a kompatibilitás korábbi konstrukciókkal

A tervezést az additív technológiával készülő centerrel kezdtem. Első lépésként összehasonlítottam a lehetséges alapanyagokat. Majd részletesen bemutattam egy generatív esettanulmány felépítését és kiértékelését Autodesk Fusion 360 szoftver segítségével. Majd elvégeztem a szükséges utómunkálati folyamatokat. Szilárdságtani ellenőrzés céljából végesem szimulációkat folytattam.

A generatív center után a hagyományos forgácsolással készült centerek megtervezése következett, amely ugyanazon metódust követte.

Végül összehasonlítottam a kész centereket egymással és a korábban használt konstrukciókkal.

Abstract

Candidate:	Dániel Bársony
Title of the thesis:	Wheel center design of a Formula Student racecar
Supervisor (external):	-
Supervisor (internal):	Martin Kaszab, research engineer

The aim of my thesis is the design of the wheel center of the tenth Formula Student racing car of the Arrabona Racing Team, a student racing team of the Széchenyi István University of Győr.

In order to carry out the design in the best possible way, I conducted a literature review on the design of rims and wheels and the related manufacturing technologies. I then conducted a competitor analysis to present the wheel and centre designs prevalent in Formula Student. I then presented and examined the wheel and center versions the team had previously used.

I first outlined the requirements and criteria that centers must meet, with the main objectives being minimum weight, safe operation, and compatibility with previous designs.

I started the design with a center made using additive technology. As a first step I compared possible materials. I then detailed the construction and evaluation of a generative case study using Autodesk Fusion 360 software. Then I carried out the necessary post-processes. I performed finite element simulations to check the strength of the components.

After the generative center, the design of the centers made with conventional notching followed the same methodology.

Finally, I compared the finished centers with each other and with previously used designs.

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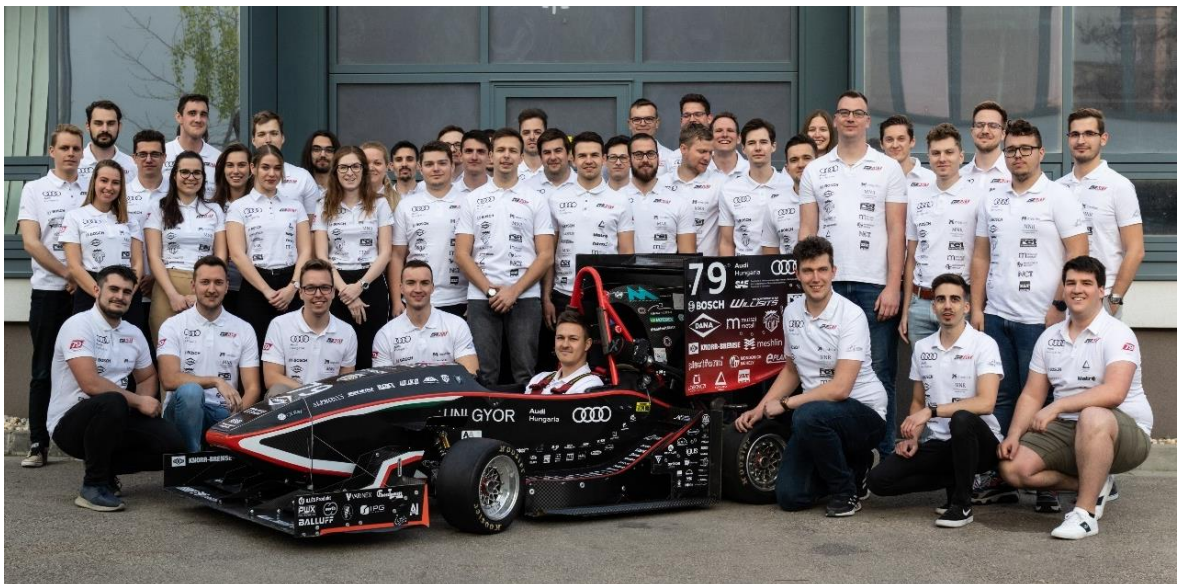
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1. Introduction

I was admitted to Arrabona Racing Team (1. Figure) in October 2021. I joined the vehicle dynamics department, which designs the suspension geometry and manufactures its components for a Formula Student (FS) race car. My main responsibility was the testing and manufacturing a hybrid composite wheel, which was designed by my predecessor in the prior season. This design uses carbon fibre reinforced polymer (CFRP) wheel rim with 3d printed aluminium wheel centers. During the 2021 season I also designed a new, lightweight centerlock wheel nut

The goal of my thesis is to develop new wheel centers, which improves on the last season's ones in every aspect, for Arrabona Racing Team's 10th generation car. For optimal use it is necessary for wheel centers to be as lightweight as possible, while still being failsafe for the safety of the driver and the rest of the car. To achieve this, I must study the different designs used in commercial use, in motorsport, and in Formula Student. I also have to research the manufacturing technologies used in wheel manufacturing, especially machining and additive manufacturing technologies. I must learn, how the physical attributes of a wheel affect a race car's performance too. Before the design phase begins, I must calculate the forces acting on the wheel. For the design of the wheel centers generative design process is used, along with manual design in CAD software. For verification of the integrity of the designed wheel centers, finite element analysis is used.



1. Figure Arrabona Racing Team members in the 2022 season ¹

¹ Property of Arrabona Racing Team

2. Formula Student

2.1. History

In 1980 Ron Matthews, an assistant professor at the University of Texas, and his colleagues decided to enter the Society of Automotive Engineers' (SAE) Mini Indy competition, in which student teams build cars using small, 5 horsepower engines and race each other similarly to the Indy 500 competition. Unfortunately, that year the series had been cancelled, so Professor Matthews and his colleagues started a similar new series, dubbed Formula SAE. The most important rule was that teams can chose any 4 stroke engines (including Wankel and Diesel engines) as long as they used a 1-inch (25,4 mm) intake restrictor.

In 1981 was the first Formula SAE (FSAE) competition held, where out of the six schools that showed interest in attendance, four took part. During the competition not only dynamic events, such as acceleration and manageability, was judged, but also static event where held. During the static events the judges scored the cars appearance and the teams' engineering creativity.

In 1998 was the first competition held outside the United States, in the United Kingdom, called Formula Student. Since then, there are multiple Formula Student competitions held yearly in Asia, Australia, Europe, and the Americas. [1]

2.2. Rules

Today the Formula Student rulebooks are over 100 pages long and released for every season. In Europe all competitions, except Formula Student UK, follow the Formula Student Germany rulebook. The rules are categorised to the following groups:

- administrative
- general technical requirements
- specific technical requirements
- technical inspections
- event rules

Administrative rules outline the basic rules of the competition, such as requirements of participation, rules of conduct, mandatory documents, and the scoring.

Most of the general technical requirements are safety related and every car must be in full compliance with them. They include the mandatory safety devices, like the shutdown button, the impact structures, and the driver restraint systems. They also outline the technical limits, in

an aim to keep the competition fair. These rules deal with the size and structure of the chassis, the dimensions of the aerodynamic devices and the movement range of the suspension.

The specific technical requirements are different for cars with internal combustion engines (CV) and cars with electric motors (EV). They also differentiate human driven cars and driverless cars (DV or DC). My thesis is based on the CV class rules but other categories may apply too. For example, CV cars' engines must be 4 stroke gasoline engines with displacement no larger than 710 cm³ and their exhaust may not be louder than 103 dB(C)s at idle and 110 dB(C)s at higher revolutions (the exact number is calculated with the average piston speed).

Event rules outline the course of the static and the dynamic events. They contain the requirement for each event, such as safety gears, minimum and maximum crew and mandatory documents. [2]

2.3. Events

In Formula Student there are two types of events, static events and dynamic events. In static events the teams present their theoretical knowledge in front of expert judges. In dynamic event the cars are in focus and scored by their performance on the courses. The maximum achievable point is 1000, 325 from static events and 675 from dynamic events. Driverless cars are scored differently (1. Table), [2]

	CV, EV	DV
Static events	325	475
Business plan presentation	75	75
Cost and manufacturing	100	100
Engineering design	150	300
Dynamic events	675	525
Skid pad	75	75
Acceleration	75	75
Autocross	100	100
Endurance	325	-
Efficiency	100	75
Trackdrive	-	200
Overall	1000	1000

1. Table Breakdown of achievable points in a Formula Student competition

2.3.1. Static events

In static events teams present their knowledge in engineering and finance. To achieve maximal points, they have to show expertise in their chosen field and professional communication skills. The judges are professionals in their categories and often work in the automotive industry or in motorsport.

- engineering design event: the teams present the judges the engineering and design decisions behind their car and its components, after the presentation the judges give feedback on the missing or unclear parts
- cost and manufacturing: the teams present that they understand even in details of the financial and time costs of their prototype vehicle. They list every part found in the car, and in a category chosen by the organisers they must price these parts and their manufacturing processes
- business presentation: the teams have to create a fictitious company based around their prototype race car, create a business plan and pitch it to the judges [3]

2.3.2. Dynamic events

During the dynamic events the judges evaluate the cars performance on the racetrack. Each event tests a different aspect of the race car, such as acceleration or track performance. At least 4 and maximum 6 drivers have to drive for each team and a single driver can only drive in 2 events. These rules aim to mitigate the superior performance of professional drivers.

- acceleration: the cars must accelerate from a standing start on a 75 m long track
- skidpan: the cars drive on a figure 8 track where they have to perform 2 laps on each circle
- autocross: the cars perform a timed lap on a 1-kilometre-long track, which includes straights, curves, and chicanes
- endurance: the main discipline, the cars drive for 22 kilometres, on the same or a similar track as autocross, after 11 kilometres there is a mandatory driver change
- efficiency: during endurance the cars fuel or energy consumption is closely monitored, the points are calculated on the consumption relative to the speed of the car during endurance [3]

2.4. Arrabona Racing Team

Arrabona Racing Team (ART) was founded in 2013, as the Széchenyi István University's

Formula Student team. During their first season in 2014, the team won an international competition, which is an outstanding achievement in Hungarian Formula Student history and yet to be repeated. The first team had only 18 members, today that number grew to over 70. The cars' design development advanced along with the team, from tube chassis with no aero package and steel suspension parts, to CFRP monocoque chassis with CFD optimised full aero package and CFRP suspension parts. The engines went from modified motorcycle engines to specifically for ART developed engines from our sister team, SZEngine engine development team. [4] [5]

The 2022 season (2. Figure) was most successful season in not only ART's history, but in the general Hungarian Formula Student history as well. The team achieved two 2nd and a 3rd overall place finishes out of the 3 highly rated competitions held in Austria, Hungary, and Germany. [4] [5]



2. Figure Achievements of the Arrabona Racing Team in the 2022 season²

3. Literature review

3.1. Nomenclature

First the nomenclature used in this thesis has to be cleared up. Wheel are assembled from the wheel rim and the wheel center. The word “wheel” is often used interchangeably with the word “rim”, but the later only covers the outer part of the wheel, on which the tire is mounted.

² Property of Arrabona Racing Team

The purpose center (or disc) is to provide a mounting surface for the wheel on the wheel hub and to transfer the torque from the drivetrain to the wheel. [6]

3.2. Wheel categorisation

To understand materials and manufacturing techniques used to produce wheels, this chapter overviews the types used on road vehicles and in motorsports. Wheels can be quite different from each other in form, in properties and in use. The used materials have the largest influence on the final product's qualities, but the manufacturing method also plays a key role.

3.2.1. Steel wheels

The least expensive material used in automotive wheels. They combine durability, great weather resistance and heat conductivity. Their weight is larger than wheels made from other materials, which affects the vehicles' handling and fuel economy. Usually they are made by stamping from sheet metal, then the rim and the center are welded together. They are most common in heavy-duty vehicles (3. Figure) and in vehicle fleets. [6] [7]



*3. Figure Steel wheels on a heavy-duty commercial vehicle*³

3.2.2. Aluminium alloy wheels

Today aluminium alloys are the most used material in wheel manufacturing. Their lightness improves vehicles' handling and fuel economy, ideal for passenger vehicles. They also offer excellent heat conductivity and weather resistance. [6]

³ <https://www.mikestruckrepair.com/product/used-steel-wheels/>

Aluminium manufacturing is well researched and proven, also offers recycling. Aluminium wheels are made either with some form of casting (gravity casting, low pressure casting) or with forging process (4. Figure). Flow Forming is a specialized method, requires a special machine that spins the cast and pulls the rim to its final shape with heat and steel rollers, offer similar qualities as forging at a lower production cost. [8]

Their use in the automotive world is quite widespread, from low quality gravity casted aftermarket wheels, through Original Equipment Manufacturer (OEM) wheels, to high end forged wheels used in motorsport. [8] [7]



4. Figure Casting and forging processes in wheel manufacturing⁴

3.2.3. Magnesium alloy wheels

Magnesium alloys are 25-30% lighter than aluminium and offer great size stability and impact resistance, but low weathering resistance. Similarly to aluminium alloys, they can be casted or forged (4. Figure). Due the high manufacturing and maintenance costs, magnesium wheels are almost exclusively used in motorsports and exotic vehicles. [7] [9]

3.2.4. Titanium alloy wheels

Titanium alloys have excellent material qualities, they are more than 2 times stronger than aluminium. They are difficult to manufacture with traditional methods and have high material costs, thus rarely used. New manufacturing techniques, such as additive methods, can utilise titanium alloys positive qualities without their drawbacks. [6] [8]

⁴ <https://www.tirebuyer.com/education/what-types-of-wheels-should-i-get>



5. Figure 2- piece wheel with 3D printed titanium center and CFRP shell⁵

3.2.5. Composite wheels

Composites, especially carbon fiber reinforced plastic (CFRP), are 1.5 times lighter and 8 times stronger than aluminium. In wheel design their lightness, high stiffness and corrosion resistance makes them an ideal material. CFRP is difficult to design, and its manufacture is cost and time heavy. Its low heat resistance can be difficult to overcome in wheel design. In case of damage they are almost impossible to repair. Due their high costs, they are most commonly found on exotic vehicles. [6] [9]



6. Figure Koenigsegg Regera's CFRP wheel⁶

⁵ <https://www.hrewheels.com/wheels/concepts/hre3d>

⁶ <https://carnival.com/koenigsegg-carbon-fiber-wheels-are-a-technological-masterpiece/>

3.2.6. Multi piece wheels

Most alloy wheels are made from a single unit, with no joints. Another common design is when the rim and the center is separately made, then welded together.

2-piece designs (5. Figure) use a separate wheel rim and center, which are held together by fasteners, this allows more flexibility than single piece units, since the rim and the center can be made from different materials (5. Figure) or with different methods. [8]

3-piece design expand the customisability of 2-piece designs by splitting the wheel rim in two halves, thus allowing the creation of combinations that otherwise wouldn't be available [6] [7]

3.3. Machining technology

Machining (or subtractive manufacturing) is a traditional and well researched manufacturing method. During the machining process small pieces of material are removed in a controlled manner from the larger starting piece of material until the desired shape is reached. Machining machines have three main types when it comes to their control. They can be controlled manually, by computer (computer numerical control, CNC) or fully automated. [10]

The main advantages of machining its ability to be really precise, down to 0.001 mm deviation from the desired dimension in the most precise conditions, the consistency to make products in the same dimension interval. Other advantages are its quick turnover rate, which makes it ideal for mass manufacturing, and the compatibility with the vast majority of materials, with the correct tools and machines. From the perspective of manufacturing cost another great advantage of machining is its prevalence and great amount of common knowledge about it, which helps to keep the cost down. [10]

The main disadvantage is the material waste, that comes from the nature of the process which increases the manufacturing costs and have to be taken into account during the design. Another disadvantage that comes from the basic principle of machining is the wear on the cutting tools, which also adds to the manufacturing costs. [10]

There are several different methods to machine materials, the most notables for metal machining are turning on a lathe and milling with a mill. [10]

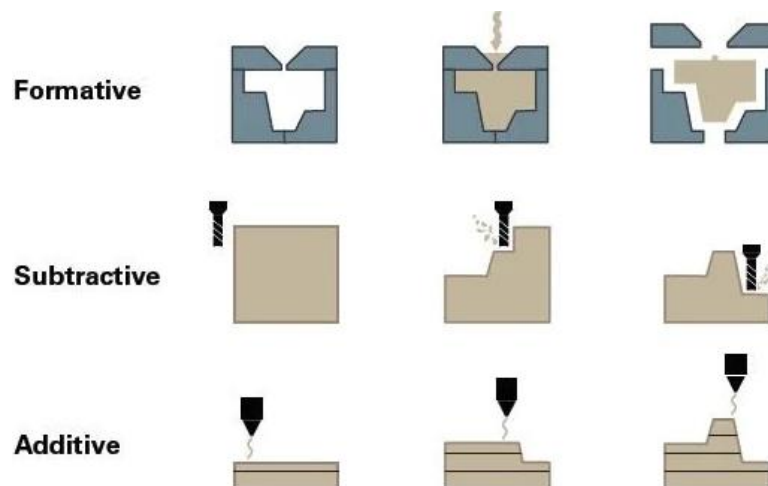
During turning the workpiece spins around its Z-axis and the cutting tool moves in x and z directions, thus creating axially symmetric products. With turning both the external surfaces and the external surfaces, if it has any, of the workpiece can be worked on. Another notable feature of turning is the ability to make threads both external and internal. [10]

During milling the cutting tool spins along the Z-axis and the workpiece moves relatively to the tool along the x, y and z axis. With this technique all 3 dimensions of the product can be worked on and combined with computer control complex geometric shapes can be mass manufactured.[10]

3.4. Additive manufacturing

Additive manufacturing (AM) is a fairly new and emerging technology. Instead of removing material from the starting piece until the final geometry is reached, like in traditional subtractive technologies, in AM the material is built one layer at a time and bonded to itself (7. Figure). Material classes that can be additively manufactured include polymers, ceramics, composites, and metals. [11] [12]

The main advantage of AM, that it allows designs to achieve geometries that would be impossible or too expensive to make with traditional manufacturing methods. Components designed to be made with AM can reach much lower weight, than if they are made with subtractive methods, while still having the same functionality. AM also makes it possible to create components with functional-grade materials. This means that different surfaces of the component that need different material qualities can be made from different materials, while still being a single component. Another advantage of AM is the relatively short manufacturing time, since there is no pre-processes and minimal post-processes. These qualities make AM ideal for rapid prototyping, where low production values and quick turnover are the most important. The main disadvantage of AM is that the production costs of components are much higher, thus the process is not suited for mass manufacturing. [11] [12]



7. Figure Simplified overview of additive manufacturing and other methods⁷

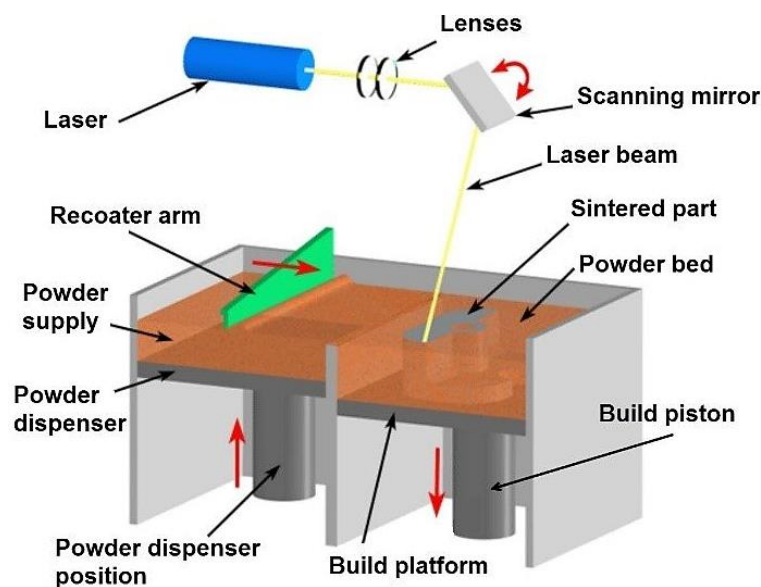
⁷ <https://www.azom.com/article.aspx?ArticleID=17901>

Today AM is getting more and more accessible for hobby enthusiast and professional manufacturers alike, thanks to fused filament fabrication (FDM) printers. With FDM technology there are large number of materials, software, and hardware to choose from and online communities of enthusiast. [11]

A more recent development in the realm of additive manufacturing is the lower cost and more widespread use of metal AM. Compared to the more commonly used polymer AM, metal AM's costs are multiple folds, so the final products prices would be much higher than with traditional manufacturing methods. Still very few companies and organisations can afford the high associated cost of metal AM. A large disadvantage of metal AM is its low accuracy, around 0.5 millimetres, which means that finished components connecting surfaces have to be machined after printing. The list of compatible metals is short, but it includes different steels, aluminium, and titanium alloys, different inocels, etc. Due its advantages and disadvantages, metal AM is often used in aerospace and space industries, but also gaining traction in motorsports. [12] [13]

3.4.1. Direct Metal Laser Sintering (DMLS)

Similar process as SLS polymer printing technology. The DMLS process' base is a high-powered (up to 1000 Watts) CO₂ laser, which can melt the material. During the process the chamber is preheated to reduce the melting time and to improve the porosity of the final component. The oxygen in the chamber is replaced with argon to improve the oxidation rate of the metal. [13]



8. Figure Illustration of Direct Metal Laser Sintering⁸

⁸ <https://www.researchgate.net/figure/A-schematic-diagram-of-direct-metal-laser-sintering-DMLS-process>

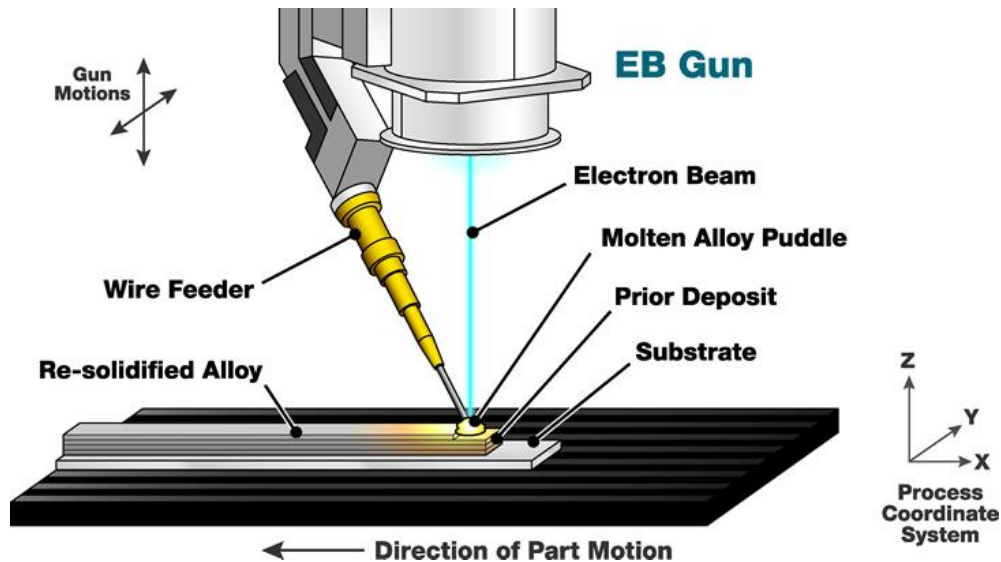
At the beginning of the process (8. Figure) the build platform is at its top position while the powder dispenser is at its lowest position. The recoater arm scatters a layer of thin metal powder, which can be 20 microns thin, across the powder bed. This part of the process is the reason of the slow speed of printing, so some DMLS machine use two powder dispensers, one on each side of the build platform, to halve the distance which the recoater arm has to cover. After the powder layer is laid the scanning mirror aims the laser the sliced cross section of the geometry and the laser melts the powder on those coordinates. As the laser is done with the melting the build platform is lowered by the layer thickness assigned to the component. These steps repeat until the last layer is done. After the process is finished the chamber have to be cooled down and the excess powder from the powder bed has to be removed, which can be reused in future operations. The component removed from the chamber still includes the support structures used to support the material during the process. During the postproduction, the support structures are removed, the required surfaces and features are machined to spec. [13] [14]

The final product has similar material properties as machined components, but the manufacturers note that the yield and tensile strength can vary depending on the direction of the printing relative to the component's geometry. The final surface quality is very rough compared to machined. These qualities have to be taken into consideration when designing a component for DMLS. [13] [14]

Today the most commonly available metal AM technology and offers the lowest production costs. Arrabona Racing Team have already used several components manufactured with this process. These include brake pedals, uprights, and the previous centers. [13] [14]

3.4.2. Electron Beam Melting (EBM)

Electron Beam Melting has two versions, a powder based, and a wire based one. Powder based EBM is quite similar to DMLS, but instead of a CO₂ laser it uses an electron beam (EB) gun. EBM machines chamber has the filled with vacuum to protect the electron beam. Compared to DMLS powder-based EBM is a faster process but produces worse fine details and surface finishes. [13] [14]



9. Figure Schematic diagram of Electron Beam Melting⁹

Wire based EBM (9. Figure) is a similar process to FDM printing, but instead melting the plastic filament with the preheated nozzle, EBM melts a metal wire with its electron beam gun. The lack of a powder bed is its main advantage, since it allows the machine to build objects much larger than with other metal AM techniques allow. Another advantage is the almost zero waste that the process produces. Wire based EBM is the fastest technology at its class, but the cost of fine details and good surface finishes, similarly to powder-based EBM. Either version of EBM is much harder to find in commercial use. [13] [14]

3.5. Effects of unsprung and rotational mass

3.5.1. Effects of unsprung mass

The unsprung mass of a vehicle is defined as the part of the mass that is unsupported by the suspension of the vehicle. In case of a Formula Student race car the unsprung mass includes the weight of wheels, tires, wheel hub, uprights, parts of the braking system, rear axles, and miscellaneous suspension components. The reduction of unsprung mass of a vehicle results in better handling in acceleration and braking scenarios, thus providing better traction and control over the vehicle. A suspension system with lower unsprung mass requires less effort to keep a constant connection between the tire and the road surface over road imperfections. [15] [16]

3.5.2. Effects of rotational mass

The tendency of a rotating object to maintain its rotating state is influenced by its rotational inertia. The magnitude of rotational inertia depends on the rotating body's mass in dimensions.

⁹ https://additivemanufa.wpengine.com/wp-content/uploads/2015/08/AM_EBDM_Illustration.jpg

Lower rotating mass and lower distance between the axis and body's edge results in lower rotational inertia. In case of vehicles, especially in case of suspensions assemblies, lower rotational mass results less torque needed to accelerate or decelerate (brake) the wheels. This improves braking efficiency and lowers fuel consumption. [16] [17]

3.6. Competitor analysis

In Formula Student one of the best places to learn is from the competition. By analysing the current trends used by the competitors, we can determine future development's usefulness in our own concept. This chapter summarises the types of wheels used by FS and FSAE teams.

3.6.1. Commercially available wheels

Many teams choose to buy wheels instead to design their own, mainly to save time and resources. There are many commercially available options from OZ Racing, BRAID and Keizer. OZ Racing and BRAID offer single piece wheels made out of aluminium, magnesium or CFRP (10. Figure 1. and 2. picture). Keizer's multi piece wheels allow teams to customize their wheels' parameters or to use their own center designs.

3.6.2. Custom alloy wheels

Custom alloy wheels offer high customisability and the opportunity to adapt wheels to unique suspension elements (10. Figure 3. and 4. picture). They are almost exclusively made out of high-quality aluminium, since the raw material prices of magnesium and titanium are too high to make them worthwhile. They are rather rare in Formula Student, because they cost similarly to hybrid CFRP wheels, while they don't offer the same weight savings.

3.6.3. Custom multi piece wheels

Custom multi piece wheels are either made out of commercially bought aluminium rims with custom machined or 3D printed aluminium centers. CFRP rims (10. Figure 5. and 6. picture) are becoming more common, since they provide large weight savings compared to aluminium rims, while they require simpler and cheaper tooling as full CFRP wheels.

3.6.4. Custom CFRP wheels

They offer the same customisability (10. Figure 7. and 8. picture) and stiffness as custom alloy wheels with much larger weight savings. Their main disadvantage is their high material and manufacturing costs. Their design and manufacturing require expertise and experience with composites and their tooling.



10. Figure Common wheel designs in Formula Student ¹⁰

3.7. Previous seasons' analysis

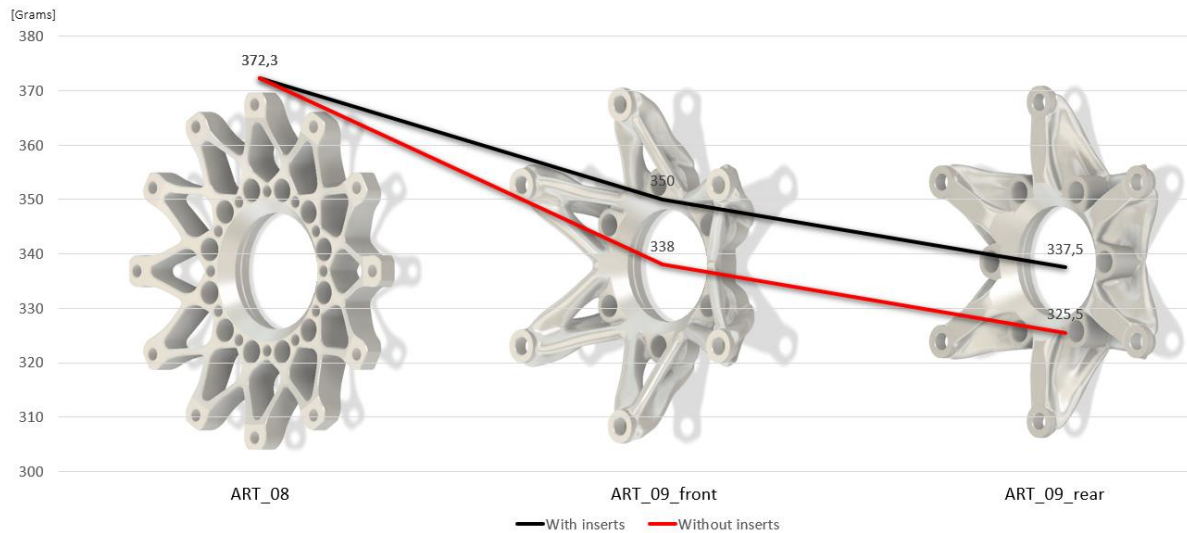
To better understand the end goal of this thesis, previous seasons' wheel assembly designs have to be explained.

Prior to 2020 Arrabona Racing Team used 13-inch wheels and tires. The wheels used were commercially bought OZ Racing wheels, first aluminium ones later magnesium ones. They served their purpose with no problem, but due to their fixed geometry suspension parts, namely the wheel hubs, had to be designed to fit them. Because of their different dimensions and the changes made since in the suspension, these wheels are irrelevant to this thesis.

For the 2020 season the team switched from 13-inch Continental to 10-inch Hoosier tyres, because the Hoosier's wider thermal operation range allowed the team to extract more performance from the car and their lower weight helped to reduce the car's unsprung mass. For the suspension geometry to accommodate the smaller wheel and tire size most of assembly's parts had to be redesigned. To be compatible with the new wheel size and suspension geometry a new wheel assembly was needed. The decision was made to use Keizer rims with custom centers, designed by the team and machined out of aluminium alloy. This 3-piece design allowed the team to use the same center design both in the front and the back with different ET (Einpresstiefe or backspacing) values. It also allowed the team to use a single custom aluminium centerlock wheel nut instead of 4 steel wheel lugs, which made it possible to use larger wheel bearings in the wheel hub. The torque was transmitted from the wheel hub to the

¹⁰ <https://media.formulastudent.de/2022>

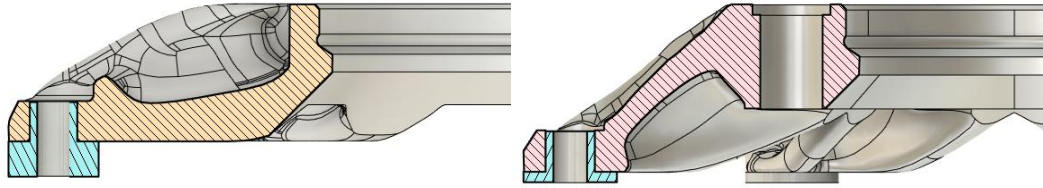
wheel through 3 aluminium pins, connecting the wheel hub to the wheel center. The new wheel assembly served during the season with no problems. The main disadvantages of this design were the assembly's higher weight compared to other options in the same size, and the use of ¼" screws and nuts, which made the acquisition of alternative fasteners (alternative material bolts and nuts, self-locking nuts) difficult.



11. Figure Weight comparison of the wheel centers used in ART's previous cars¹¹

For the 2021 season the Vehicle Dynamics department's goal was to optimise the suspension components and to reduce the unsprung weight of the car. The most cost and time effective way was determined to replace the aluminium wheel assembly with a hybrid CFRP assembly. The design uses two CFRP rim halves and topologically optimised aluminium wheel centers, made with additive manufacturing techniques. The design was developed to be compatible with the previous aluminium assembly. The rim's outer geometry follows the Keizer rims used in the rear axle, so different centers had to be designed for the front and the rear axles. The centers were made by one of the team's sponsors using DMLS printing technology. They use 6 spoke designs with unique geometries, due the use of topological optimisation. The holes for the mounting fasteners are in press-fitted inserts instead of the centers themselves, for better stress distribution and ease in case of the fasteners size have to be changed. The rear trackwidth was widened by 10 millimetres, for better cornering stability, after the centers' manufacture, by making new inserts, each 5 millimetres wider.

¹¹ Property of Arrabona Racing Team



12. Figure The different inserts used in the rear (left) and the front

For the rims manufacturing custom designed 5-piece composite laminating mold was designed. This mold includes a positive mold and two negative mold rims, all machined out of aluminium. Due pandemic related shortages and delays the mold wasn't ready in time to figure out the details of the laminating process. In 2022 the lamination process and the mold were improved, so a full set was hand made by the lamination subgroup of the team. During the testing period the wheels were tested and determined to be safe for use in competitions. In the after-season evaluation the hybrid CFRP wheel set was designated as a success and future resources were allocated for its development. Due the compatibility with the aluminium wheel assembly, this wheel design also suffers from the disadvantages of 1/4" fasteners. The final wheel assemblies' weight was higher than planned, due some manufacturing problems. The weight saving was only 400 grams compared to the previous design, instead of the planned 600 grams.



13. Figure The hybrid CFRP wheel used in 2022 and its laminating mold¹²

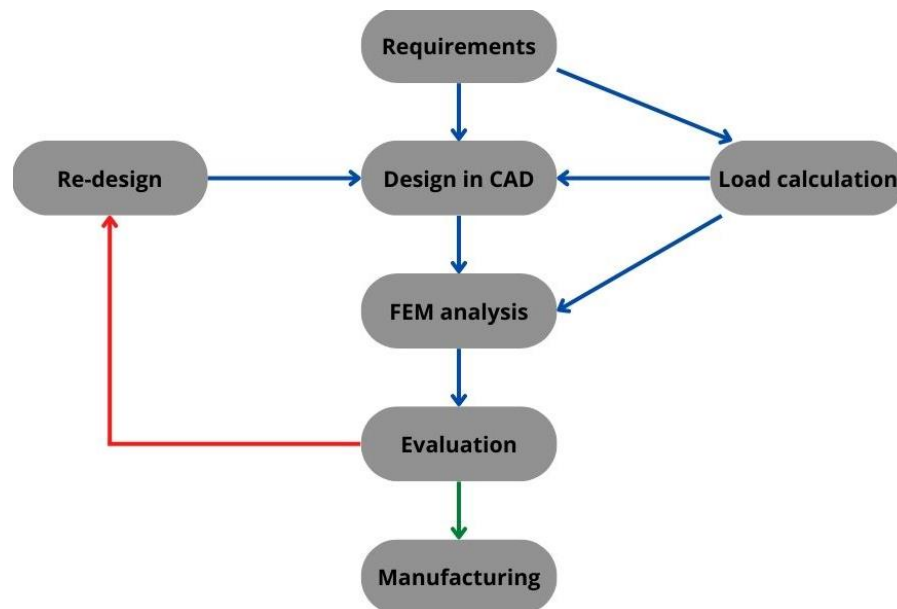
¹² Property of Arrabona Racing Team

4. Design process

In this part of the thesis the whole design process is followed through, from the methodology behind the design process to the introduction of the final product.

4.1. Methodology

This chapter clarifies the work methodology used to design the wheel centers. This thesis uses the iterative design methodology. The iterative design methodology requires a cyclic process which is made out of prototyping, testing, and analysing. In this thesis prototyping is done in Autodesk Inventor and Fusion 360 CAD software, the testing and analysis in Fusion 360's in-built FEM module.



2. Table Iterative design work flowchart

The generative design process is similar to the aforementioned iterative design, as in a cyclic progress of prototyping, testing, and analysing, but instead of the designer an algorithm does this cyclic work. It is also similar to topological optimisation (TO), but while in TO the algorithm begins with a human made model with loads and constraints, the generative process only requires loads and constraints. [16]

4.2. Requirements

4.2.1. Rules concerning wheels

Firstly the rules, in which the wheel centers are constructed, have to be clarified. It is important to all parts of the race car to be in compliance with the rules, because one rule

infringement can result in disqualification or the need to use of inferior parts.

“T 2.4 Wheels

- T 2.4.1 Any wheel mounting system that uses a single retaining nut must incorporate a device to prevent loosening of the nut and the wheel. A second nut (“jam nut”) does not meet these requirements.
- T 2.4.2 Standard wheel lug bolts and studs must be made of steel and are considered engineering fasteners. Teams using modified lug bolts, studs or custom designs will be required to provide proof that good engineering practices have been followed in their design. Wheel lug bolts and studs must not be hollow.
- T 2.4.3 Aluminium wheel nuts may be used, but they must be hard anodized and in pristine condition.” [2]

"T 10.1 Critical Fasteners

- T 10.1.1 Critical fasteners are defined as bolts, nuts, and other fasteners utilized in the primary structure, the steering, braking, driver’s harness, suspension systems and those specifically designated as critical fasteners in the respective rule.
- T 10.1.2 All threaded critical fasteners must be at least 4 mm metric grade 8.8 (OEM parts 3 mm metric grade 8.8), equivalent or of that specified in the referencing rule, whichever is larger.
- T 10.1.3 All threaded critical fasteners must be of the type hexagon bolts (ISO 4017, ISO 4014) or socket head cap screws (ISO 4762, DIN 7984, ISO 7379) including their fine-pitch thread versions. Alternative fasteners are permitted if the team can show equivalence.
- T 10.1.4 Any bolted joint in the primary structure using either tabs or brackets, must have an edge distance ratio “ e/D ” of 1.5 or greater. “ D ” equals the hole diameter and “ e ” equals the distance from the hole centerline to the nearest free edge of the tab or bracket. Any tabs attaching suspension members to the primary structure are not required to meet this rule. ” [2]

4.2.2. Design requirements

The aim of this thesis is to improve the wheel assembly for Arrabona Racing Teams next Formula Student race car. The hybrid CFRP wheels were successful in reliable operation and in lowering the unsprung mass of the suspension. Due the extreme mechanical loads used when designing the wheels, so there is possibility for further weight saving without sacrificing the

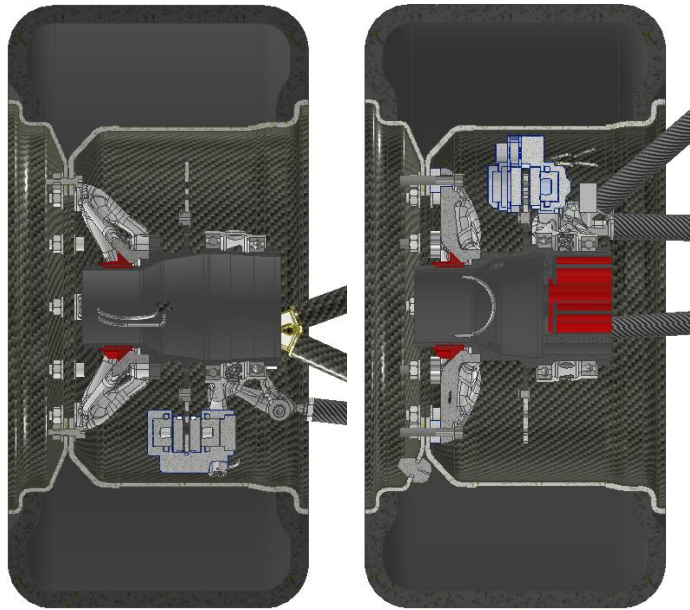
reliable operation of the wheels. The team's leadership decided that the manufacture of a new set of lamination molds would be too expensive for this season's budget, so the CFRP wheel rims will be unchanged for this season.

Since only one set of 3D printed wheel centers were made, there is a need for another 2 set for newly made CFRP rims. The front centers' geometry remains unchanged, so it isn't necessary to redesign it. The rear centers geometry did change during last season, by new inserts, so this will be included in the new design.

From previous years' experience, additively manufactured components conceal high risk in terms of missed deadlines, because the manufacturers can only make the team's components in a certain time window with their other projects. To be prepared for every outcome a set of machined centers will be designed as well.

Design requirements:

- failsafe operation
- minimum safety factor of 1.2
- compatibility with the suspension geometry (14. Figure)
- compatibility with the wheel hub design (14. Figure)
- compatibility with already existing CFRP wheel rims (14. Figure)
- use of metric M6 fasteners
- can be converted to use 1/4" fasteners if needed
- global displacement under 0.2 millimetres
- be as cost effective as possible
- the 3D printed design be 10% lighter than the previous one
- the machined design can be manufactured without a 5-axis CNC machining center
- the machined design's weight is within 120 % of the previous 3D printed design's weight



14. Figure The front (left) and the rear (right) wheel assemblies

4.3. Load case determination

To properly design the wheel centers and accurately simulate their structural integrity, the mechanical loads have to be determined first. The original aim of this thesis was to use validated data from strain gauges mounted on the steel A-arms of the car, recorded while testing in a competition like environment. Unfortunately the data recorder of the strain gauges was unrepairable damaged during its testing due some electrical faults.

4.3.1. Mechanical loads from simulation

Since information about the suspension loads from the suspension strain gauges couldn't be extracted, instead data from IPG Carmaker software was used. IPG Carmaker is a multi-purpose software, which among others, simulates the lap time of a chosen vehicle in a chosen scenario, while also simulating and recording the forces acting on the vehicle. To conduct such a simulation the car and the track have to be defined and built up in the software itself, but in this case, they are already done from last season.

The normal forces of the tires' contact patch will be used to calculate the loads of the centers. To calculate the largest forces that can act on the wheels extreme scenarios have to be defined, that have close to zero chance of occurring during normal competition use.

The first scenario's purpose is to calculate the highest possible longitudinal forces of the wheels. It is an acceleration to maximum speed on special, high grip tarmac, then breaking to complete standstill, still on the same tarmac. This couldn't happen during a Formula Student dynamic event because the acceleration track is only 75 metres long according to the rules. 75

metres is not long enough for the car to reach its maximum speed. Though there are some competitions that use higher grip tarmac on their acceleration track, for example Formula Student Austria.

The second scenario is a traditional skidpad with a 30-meter diameter. A skidpad is a circular track, which is used, among other things, to test vehicles' lateral acceleration. This simulation will answer, what is the maximum lateral force acting on the contact path of the car. This scenario also could never happen in a competition, only in a controlled testing environment, because the standard formula student skidpad is not a 30-meter diameter circle, but an eight-figure consisting of two 21 m diameter circles.

To calculate the largest forces acting on the wheel patch at the same time, the virtual car was simulated running through the Formula Student Germany autocross track in ideal conditions. This simulation has to be done separately, because the forces simulated in the previous scenarios can't act at the same time.

The following table (3. Table) lists all the forces from the different simulated scenarios. The separately acting and the at the same time acting forces are listed individually. Since the separately acting forces will be used at the same time instead of the same time acting forces their difference is listed under the safety factor column.

Name of the force	Acting separately [N]	Acting at the same time [N]	Safety factor
Longitudinal (F_x)	+/-2700	+950	2,8
Lateral (F_y)	+/-2300	+1800	1,25
Vertical (F_z)	2200	1500	1,45

3. Table The forces acting on the contact part of the wheels

4.3.2. Validation

Before the forces listed in the aforementioned table could be used in FEM analysis and generative design, they have to be validated. This is important since the wheels are a critical part of the car and their failure can lead to large amount of financial damage or even to the pilot's injury.

For the validation data from the car's onboard telemetric system, recorded during Formula Student Germany (FSG), was used. The maximal longitudinal and lateral acceleration values were compared to the same values extracted from the telemetric recorder.

	IPG Simulation [G]	FSG [G]	Difference [%]
Peak longitudinal acceleration	-1,92	-1,89	+1,59
Peak lateral acceleration	2,05	2,11	-2,84

4. Table Comparison between simulated and real acceleration values

As the table (4. Table) shows the car in the IPG simulation reached similar peak acceleration values as it did in real life. These peak values are only present for a few thousand of a second both in the simulation and in real life, but the sustained loads are following a similar path too. The minimal difference between the simulated and the real results could come from the way IPG Carmaker replicates the track it uses. While the real FSG racetrack is laid out with cones, so it is impossible to cut corners without penalty, the one built in IPG looks like a traditional racetrack with runoff areas, so the virtual driver can minimally cut corners.



15. Figure High value load case during Formula Student Austria¹³

4.3.3. Clamping force

To calculate the clamping force acting on the center proper calculations have to be performed. The single centerlock wheel nut requires larger locking torque than regular wheel nuts or wheel bolts, from 120 Newton meters up to 200 Newton meters.

The following formula gives a good estimate the torque required to reach the predetermined preload:

¹³ property of Arrabona Racing Team

T: required torque

F_{cl} : required clamping force

d_m : average between the major and minor diametres

f: coefficient of friction

d_c : mean collar diameter

$$T = \frac{F_{cl} \times d_m}{2} \times \left(\frac{l + \pi \times d_m \times \sec \alpha}{\pi \times d_m - f \times l \times \sec \alpha} \right) + \frac{F_{cl} \times f_c \times d_c}{2} \quad [16]$$

Since $\frac{l}{\pi \times d_m} = \tan \lambda$ and $d_c = \frac{(d + 1,5d)}{2} = 1,25d$, the equation can be rearranged to the following:

$$T = \left[\frac{d_m}{2 \times d} \times \left(\frac{\tan \lambda + f \times \sec \alpha}{1 - f \times \sec \alpha \times \tan \lambda} \right) + 0,625 \times f_c \right] \times F_i \times d \quad [16]$$

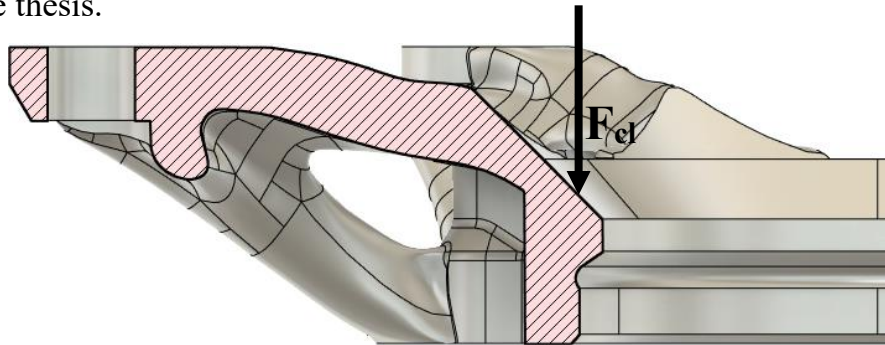
By introducing K torque coefficient, which equals the content of the square bracket, the equation can be simplified to the following:

$$T = K \times F_{cl} \times d \quad [16]$$

Rearrangement to the clamping force results the following equation, which can be used to calculate the required clamping force:

$$F_{cl} = \frac{T}{K \times d} = \frac{200 \text{ Nm}}{0,2 \times 0,056 \text{ m}} = 17857 \text{ N}$$

The clamping force acts parallel to the axis of the wheel hub and the centeclock nut (16. Figure). An FEM simulation of the clamping force will be shown at the corresponding chapter of the thesis.

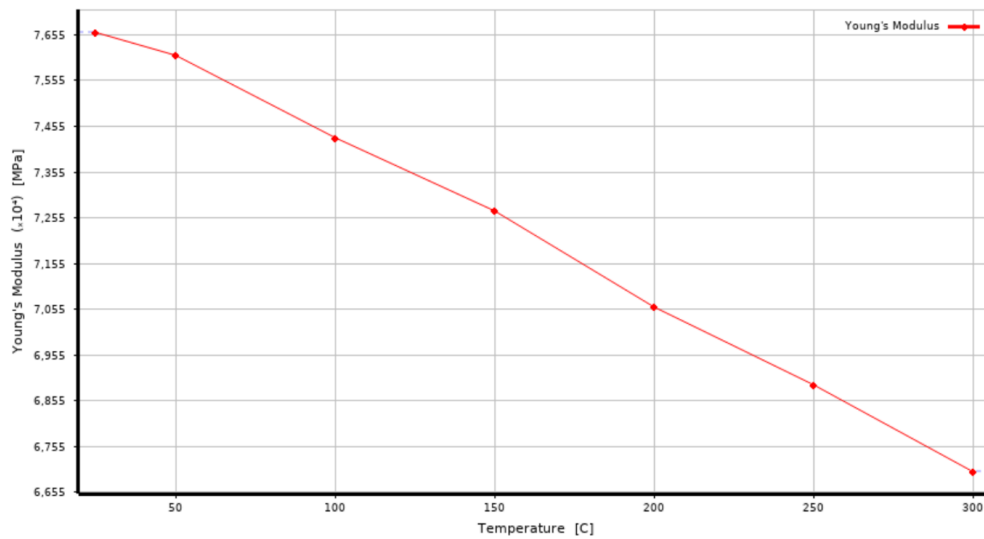


16. Figure Illustration of the clamping force acting on the center

4.3.4. Thermal loads

During the design of all components, that exist in the vicinity of heat sources, the thermal loads of have to be taken into consideration. Heat can change a component's material's mechanical properties, most importantly the yield strength and tensile strength. [19]

From previous testing experience the team has documented that while the brake disks can reach temperatures above 400 °C, the wheels surface temperature have never risen above 50 °C. Today the pre-defined material properties in FEA software include their change depending on their temperature (17. Figure), so this variable will be used during the FEM simulation of the centers.



17. Figure AlSi10Mg Young Modulus-Heat graph¹⁴

4.4. 3D printed design

Last season's 3D printed wheel centers were a success, so this design builds on them and improves it while adopting it to this year's car. From last season the manufacturer and the manufacturing method is carried over, so this design incorporates them.

4.4.1. Material selection

The material selection is critical part of all components design process. Mistakes in material selection can lead to component failure, redesigns, wasted material and human resources. The used material's mechanical properties decide the final component's properties and price. When a material cost is taken into consideration, it is important to remember, that not only the raw materials purchasing price have to be paid. Some materials are harder to form

¹⁴ Ansys Workbench 2020

and to machine than others, so the cost of the components made out of them can be considerably higher.

In today's additive manufacturing the list of usable metals is rather short, but it keeps expanding. The limiting factor is usually the additive manufacturers themselves. The machines used by them are only certified for certain materials and switching between the certified materials is cost and time consuming.

To make the best decision about which material to use, their mechanical properties (tensile strength, yield strength, elasticity, etc. (5. Table), costs, knowledge in the team already about them and their current availability in retail are taken into consideration

A decision matrix was made to illustrate the different decisional factors (6. Table). In the matrix the lowest rating is 6, while the best is 1.

Material	Density [g/cm ³]	Tensile strength [MPa]	Yield strength [MPa]	Modulus of elasticity [GPa]
Aluminium AlSi10Mg	2.68	460	240	70
Aluminium AlSi7Mg0.6	2,67	390	210	70
Stainless Steel SS316L	7,95	530	340	180
Stainless Steel C465	7,84	1400	1300	195
Titanium Ti6Al4V	4,39	980	900	110

5. Table Mechanical properties of additively manufacturable materials [19] [20]

Factors	Aluminium AlSi10Mg	Aluminium AlSi7Mg0.6	Stainless Steel SS316L	Stainless Steel C465	Titanium Ti6Al4V
Mechanical properties	3	4	5	2	1
Potential weight	2	3	5	4	1
Price	3	2	1	4	5
Possessed knowledge	1	2	4	5	3
Availability	1	5	2	5	3
Sum	10	16	17	20	13

6. Table Decision matrix used to decide the material used in the 3D printed center

As base material AlSi10Mg was chosen. The deciding factors where, as in the decision

matrix shows (6. Table), were that it is available at most of the additive manufacturers and the experiences within the team with this material. Many components were designed with it in mind, and they have proven to be reliable. AlSi10Mg also possesses excellent mechanical properties, ideal for making lightweight components.

AlSi7Mg0.6 offers similar, but smaller advantages as AlSi10Mg, at a lower price. Unfortunately it is harder to find, since few additive material suppliers stock it, especially in Hungary.

Ti6Al4V would be also a great choice, for its outstanding mechanical properties. Its low density and high strength make it one of the best materials to use in weight critical areas, such as in motorsport or in aero industries. Titanium's main drawback is its high price and low availability, since only a few specialised dealers provide it. If one of the team's partners would offer to provide the team the ability to print Ti6Al4V, with no extra charged, it would be the preferred material for its superior properties compared to AlSi10Mg, but at commercial pricing, or even with rebates, it doesn't worth the extra costs.

Stainless Steel SS316L is a low-cost option for additive manufacturing. It has good corrosion resistance and mechanical qualities. Unfortunately it isn't ideal for designing lightweight components.

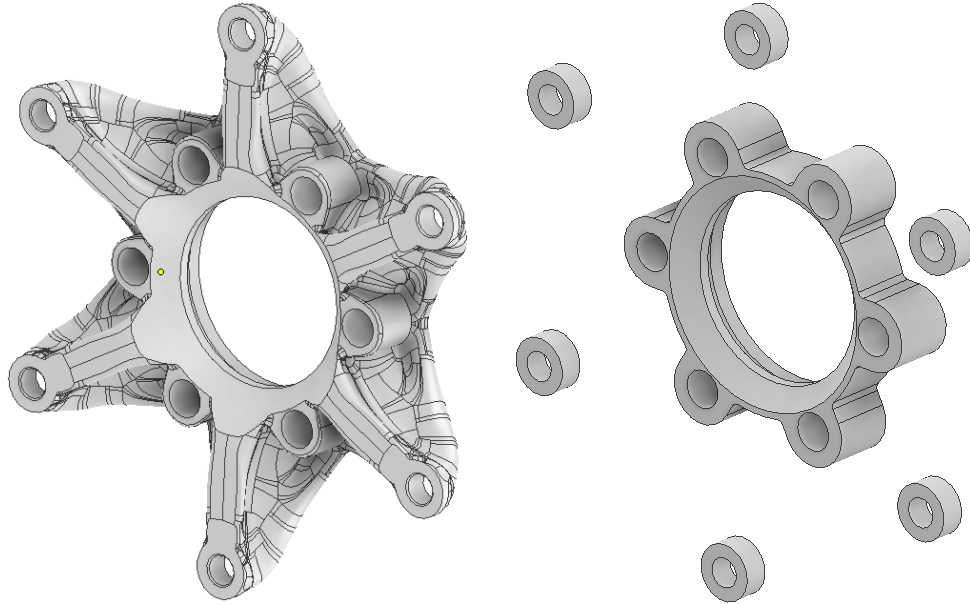
Stainless Steel C465 is an excellent material for additive manufacturing, because of its outstanding mechanical qualities. Components made out of this material additively could achieve lighter weight than similar components machined out of aluminium alloy. Other available and with additive manufacturing methods compatible materials can offer even lower weight and C465 relatively high price makes it an unpreferable choice.

4.4.2. Generative process

For the generative design process Autodesk Fusion 360 CAD software was selected. Its main advantages are its deep integration with Autodesk Inventor, the CAD software uniformly used in ART, and its built-in generative design, finite element analysis (FEA), and topological optimisation (TO) modules. Another advantage of Fusion 360 is the cloud-based computing. This means the studies and simulations defined on the user's computer are sent to Autodesk's central supercomputer for computing and only the results are sent back. This results that any computer that can run Fusion 360, can run these simulations and there is no need for high performance, workstation-grade computers.

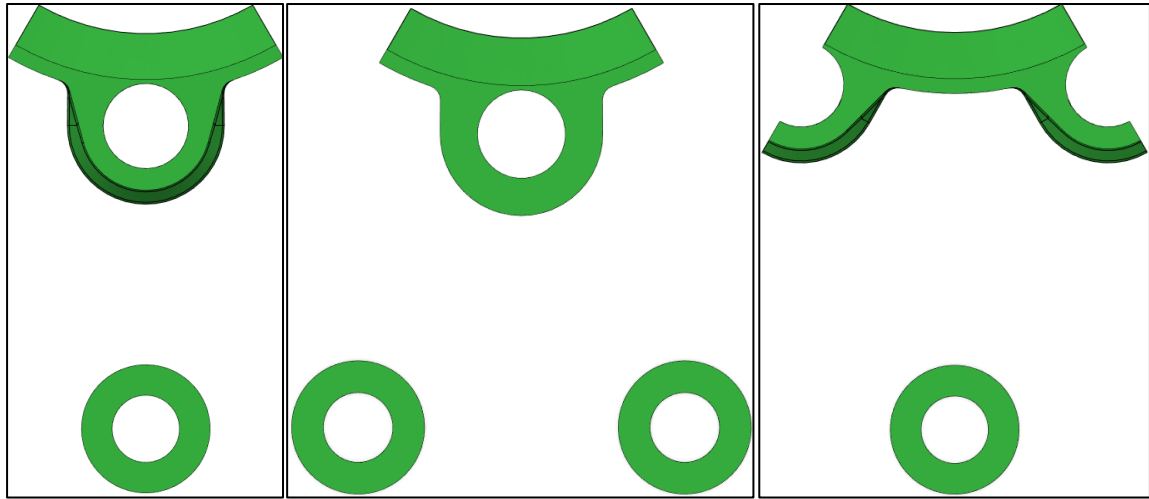
4.4.2.1. Pre-processes of the generative studies

Before the iterative design process could begin last season's model has to be reduced only to the features that will remain in the new design (18. Figure). This helps to visualise the boundaries in which the new features have to be designed and clearly shows where the new geometry can be designed.



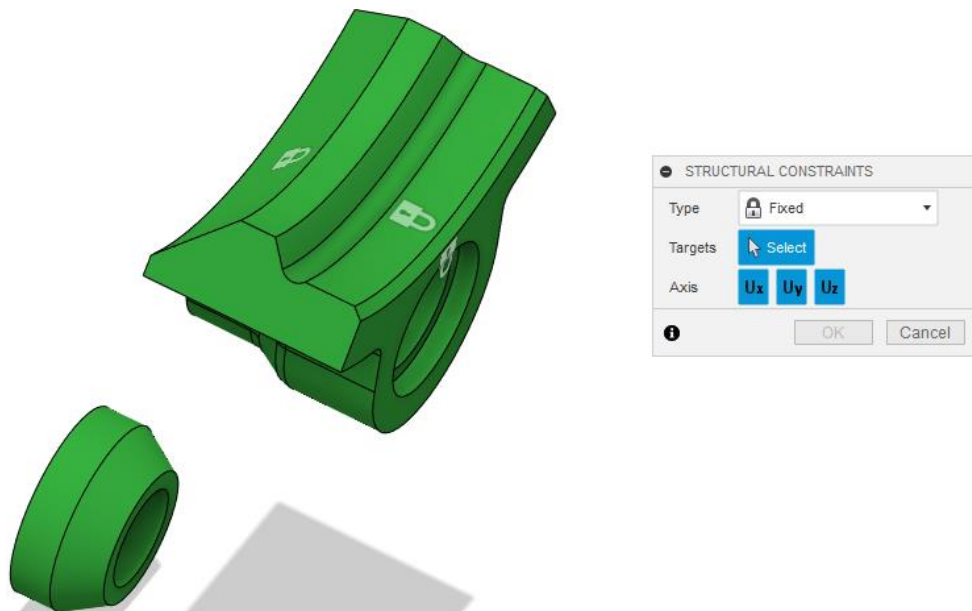
18. Figure The last season's center and its reduced geometry

The generative design process requires several elements to function. The first is the preserved geometry. These geometry parts will be connected by the generative process and will be included in the final model. For the best result several different versions have been made. There have been made 6 and 12 spoke variants, with different spoke positions and variants with or without relief chamfers. Then these designs were reduced to their 1/6 (19. Figure), equating a single spoke. This is needed because the larger forces only effect a single spoke (or a pair of, in case of a 12 spoke design) and the computing time of the process can be severely reduced.



19. Figure Three different preserved geometry used during the generative process

The next step in the generative process is determining the load cases which affect the final component. This is done similarly to a FEM analysis, with structural constraints and loads. First the structural constraints have to be specified. These can be defined on the model's edges, flat or curved surfaces and can be defined which degrees of freedom are fixed. It is important to properly select these constraints, because they have critical influence of the final results' properties. For the center the connecting surfaces to the centerlock nut and the wheel hub are constrained on all of their degrees of freedom (20. Figure). This means that these surfaces can't move in any direction and can't rotate along any of their axes.



20. Figure Constrained surfaces on the center

Next are the structural loads, which as with the structural constraints, can be applied on edges or on surfaces. To do this the contact patch's normal forces have already been defined (3.

Table), but to correctly simulate them, the loads transmitted to the center have to be calculated. They are calculated for the pitch circle diameter of the center. The following values and equations were used:

Screws pitch circle diameter on the center = 171,2 mm

Distance between the contact patch and the center point = 205,74 mm

$$F_{xc} = \frac{F_x \times 205,74}{\frac{171,2}{2}} = \frac{2700 \times 205,74}{85,6} = \pm 6490 \text{ N}$$

$$F_{yc} = \frac{F_y \times 205,74}{\frac{171,2}{2}} = \frac{2300 \times 205,74}{85,6} = \pm 5528 \text{ N}$$

$$F_z = 2200 \text{ N}$$

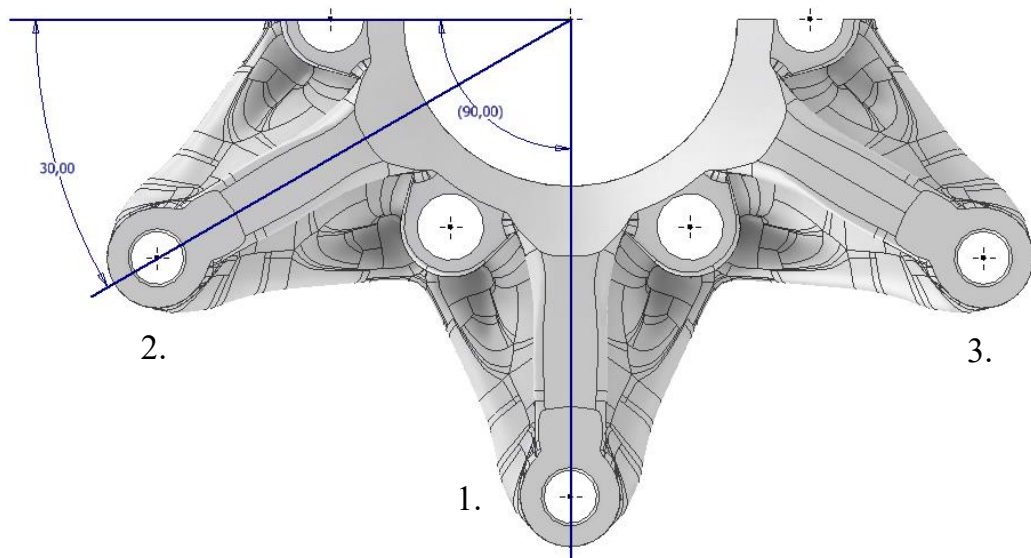
These converted forces on the pitch circle are distributed between the spokes sinusoidally. Because of this where the forces perpendicular to the spoke, the loads are zero, and when they are closest to the contact patch, they reach their maximum. To calculate the loads for the different spoke positions, the following equations were used:

$$F_{x2,3} = \frac{F_{xc} \times \sin 30^\circ}{2} = \frac{6490 \times \sin 30^\circ}{2} = 1622 \text{ N}$$

$$F_{x1} = F_{xc} - (F_{x2,3} \times 2) = 6490 - (1622 \times 2) = 3246 \text{ N}$$

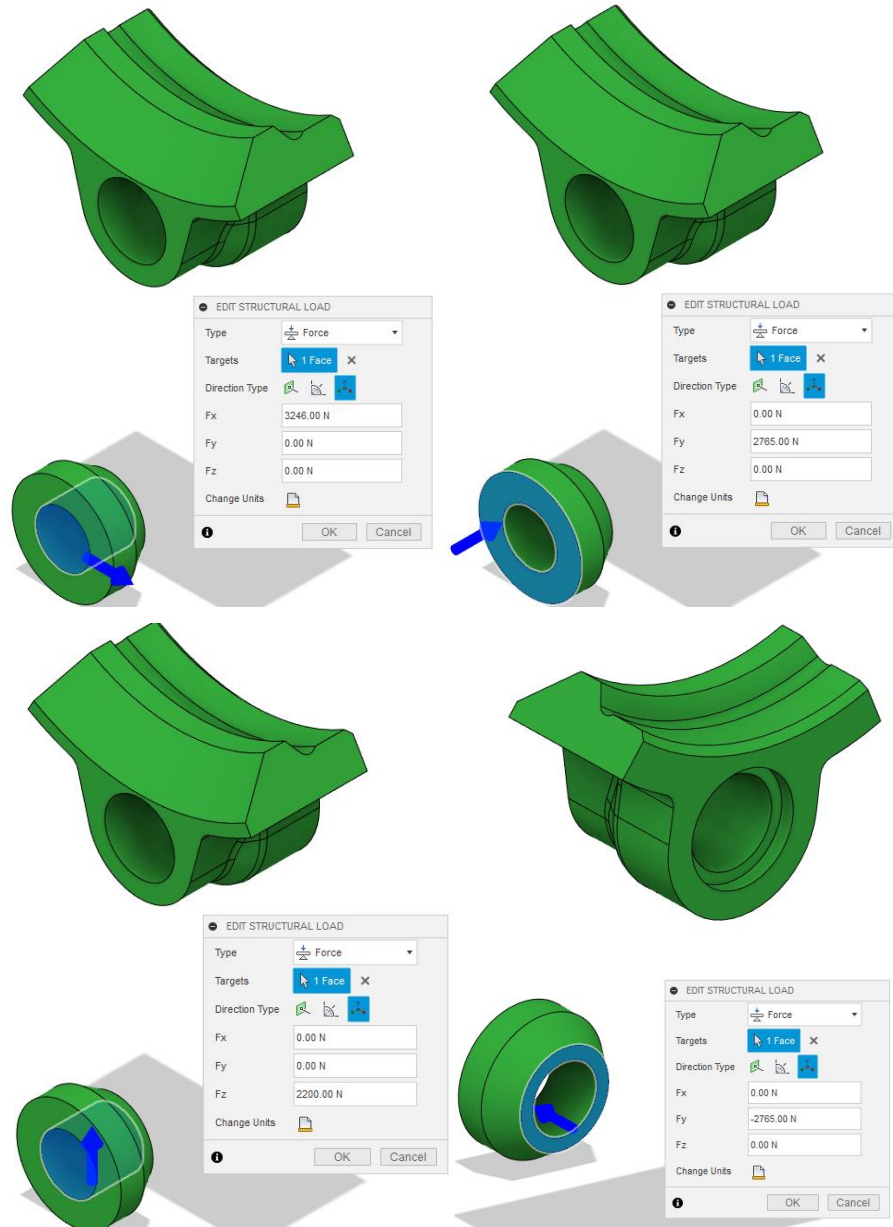
$$F_{y2,3} = \frac{F_{yc} \times \sin 30^\circ}{2} = \frac{5528 \times \sin 30^\circ}{2} = 1381 \text{ N}$$

$$F_{y1} = F_{yc} - (F_{y2,3} \times 2) = 5528 - (1381 \times 2) = 2765 \text{ N}$$



21. Figure Visualization of the calculations

For a single generative study multiple load cases can be assigned. To simulate all the loads that can affect the centers 9 different load cases are applied to the study. Each load case contains either a previously calculated maximal force or a combination of those forces. The generative module's algorithm generates result geometries based on these forces, so their correct application is critical. The longitudinal and vertical forces are applied to the connections point to the rim (22. Figure A and C), while the lateral forces are applied to the connecting surfaces to the rim (22. Figure B) and to the bolt and its washer on the other side (22. Figure D).

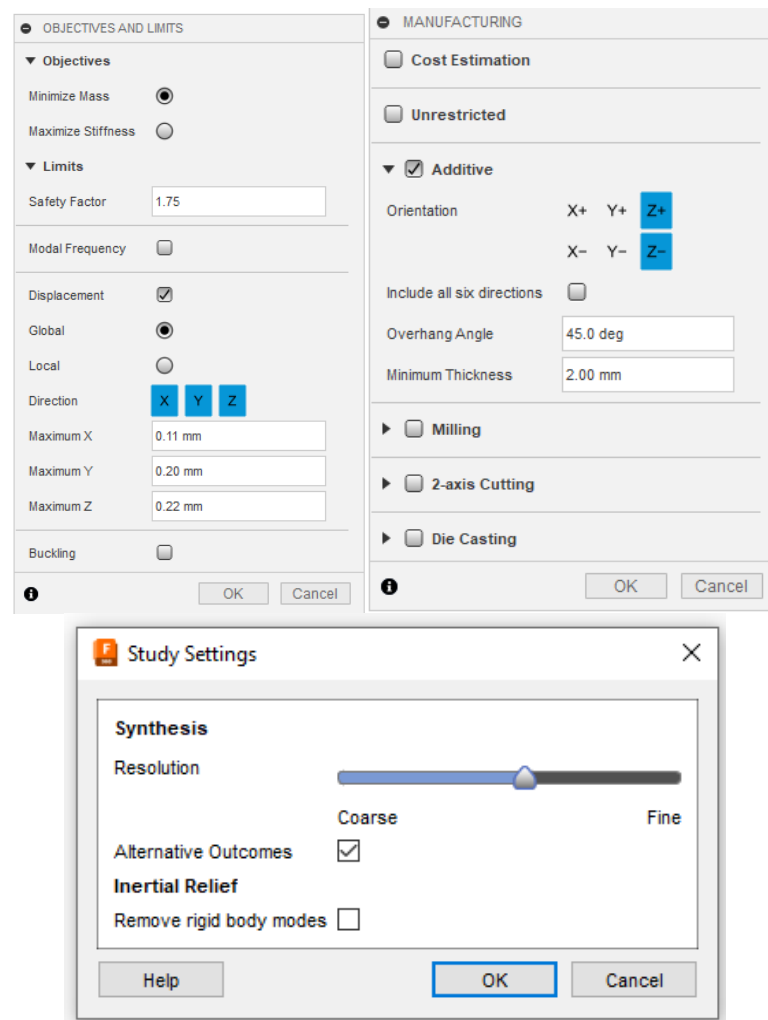


22. Figure The loads applied to the generative study

Next step is to adjust the study's settings and criteria. The metrics are critical for the properties of the study's finished geometries, so its outmost important to properly set them for the simulated case. First the study's objective has to be set. There is to main objectives to choose

from, either lowest final mass or maximal final stiffness can be chosen. Due current and previous experiences it can be stated that this choice has minimal effect on the final geometries' properties. It has been observed that the “maximise stiffness” option sometimes results final geometries with worse displacement values than the “minimise mass” option. Another option on the same tab is to maximise the displacement either globally or locally.

Another parameter that can be changed is the minimal safety factor (23. Figure). In ART the planned minimal safety factor for machined components is 1.25. However it was also observed that Fusion 360's safety factor calculations are inaccurate when it comes to additively manufactured components. So due this inaccuracy and the nature of additively manufactured components (surface roughness, sintering imperfections) the minimal safety factor of the generative study is set to 1.75.



23. Figure The studies setting used for the center

Another important factor is the manufacturing method (23. Figure). This setting has large influence on the final geometry, because the algorithm takes it into consideration how the

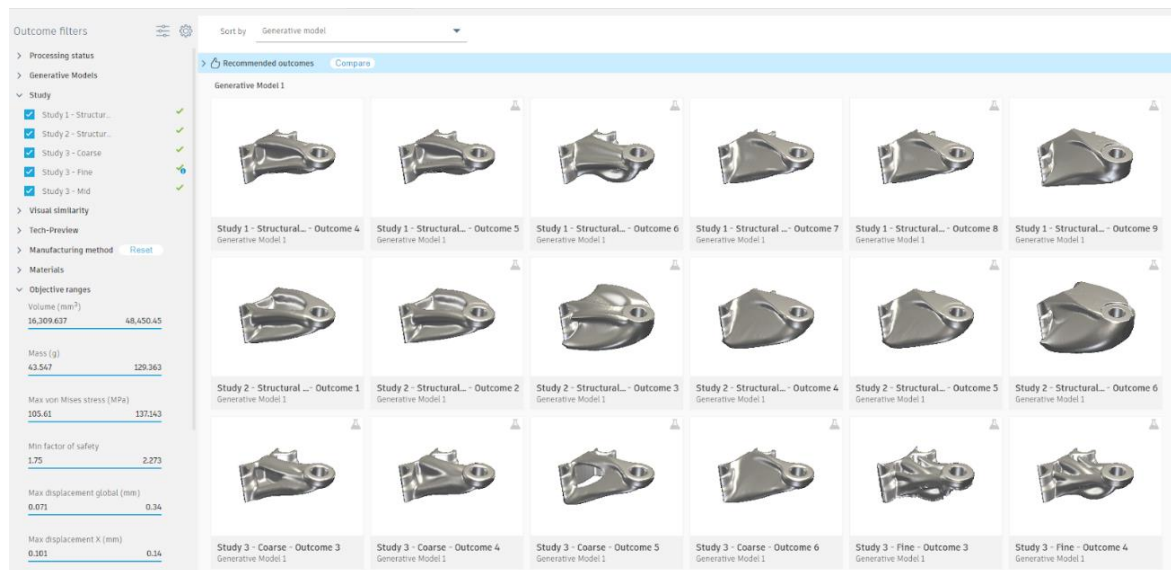
component can be made. Fusion 360 offers multiple option when it comes to manufacturing methods. The first is “unrestricted”, which isn’t constrained by any manufacturing restrictions and can achieve rather extreme geometries. There are traditional machining methods, namely CNC milling in 2,5-axis, 3-axis and 5-axis variety. For simpler components there is the option for 2-axis cutting. A new addition is the experimental option of die casting. For the center’s studies the additive manufacturing option was used. Under the additive option there are several settings that have to be accurately set, so the final component can be made with real metal AM machines too. The first is the orientation of the printing. For the center the Z-axis was chosen in both directions. The next options are the overhang angle and the minimum thickness of the material. These were set on the values recommended by ART’s manufacturing partner.

Next is defining the material properties. Fortunately the Fusion 360 Material Library already contains the previously selected AlSi10Mg. The predefined material properties were validated with data sheets from a 3rd party material manufacturer and match the material properties used in the decision matrix previously (5. Table).

The final parameter to configure is the studies’ “resolution” (23. Figure), meaning the element size used during the generative studies. This is an important part of every FEM simulation, since it decides how long the computing time will be and severely effects the outcome of the simulations. In Fusion 360’s Generative design module this is done with a slider between “coarse” and “fine”, instead of actual element sizes. For the center’s studies 5 different “resolution” settings, ranging between 100% “coarse” and 100% “fine”, are running at the same time to maximise the available pool of results.

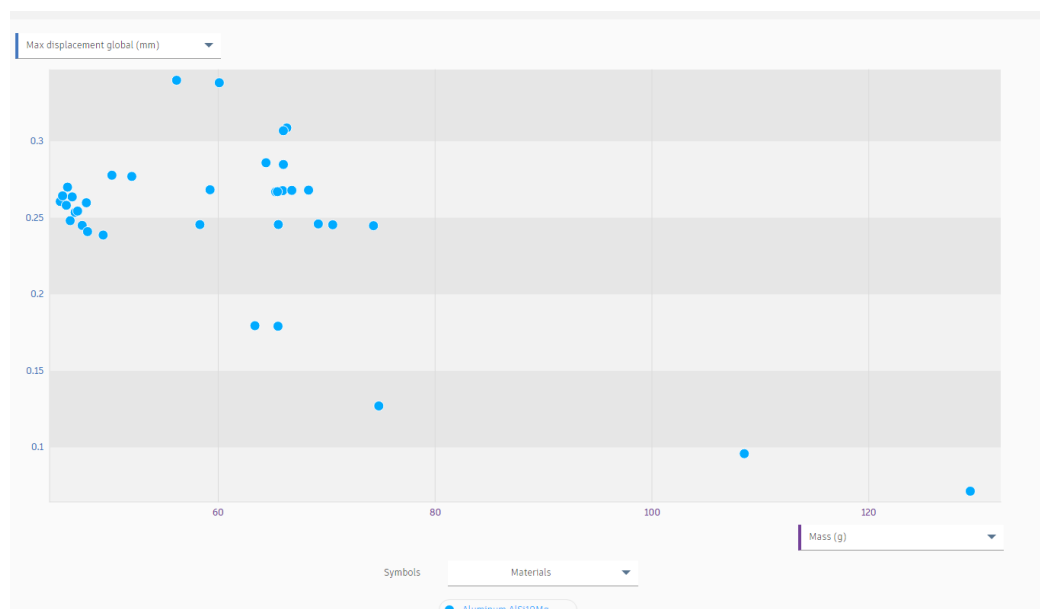
4.4.2.2. Analysing the results

After the settings are set, the generative studies are sent to Autodesk’s supercomputer for computing and the results are sent back. This can take between 1 hour and over 1 day depending on the choices made within the setting. Thanks to the multiple preserved geometries and settings used with those geometries the generative studies resulted over 50 potential outcomes and most of them finished under 1 day. A single study results on average 6-10 results (24. Figure).



24. Figure Results of multiple generative studies

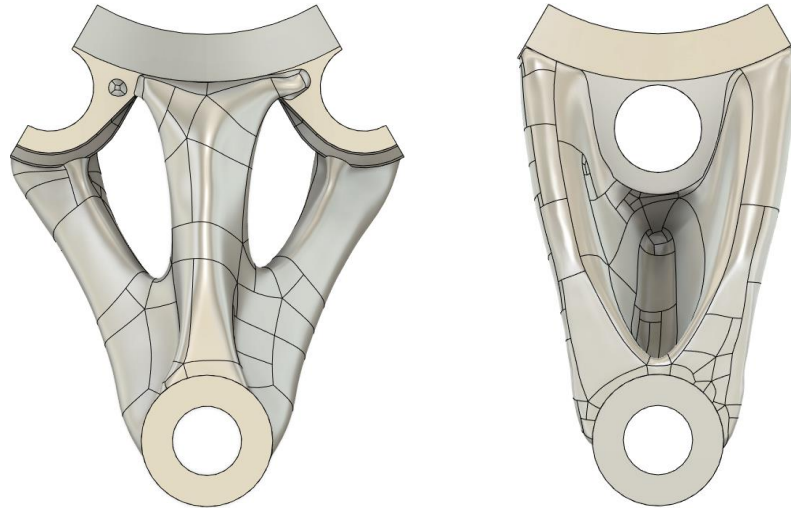
To help choose from all the results the most optimal one, they can be listed based on their factor of safety, mass, or displacement. Unfortunately one factor isn't enough to choose an optimal geometry, all of them have to be taken into consideration. To help this process Fusion 360 has a “scatter plot view”, which visualizes the results in a graph like interface. The axes of the graph can be changed to display the chosen aforementioned factors. To evaluate the centers mass and displacement were chosen as X- and Y-axes. The factor of safety wasn't taken into consideration since all of the results had a safety factor of at least 1.75.



25. Figure Scatter plot view of the generative study's results

In addition to all the different results, a single completed geometry also includes multiple iteration of itself since it usually takes the generative module between 10 and 30 iterations to

reach the optimal one. So for the best result it is necessary to check all the results and turn back some previous iteration. Based on the mentioned factors and method the following (26. Figure) raw geometries are chosen for further investigation and testing. Their properties and the differences between them are shown in the following table (7. Table).



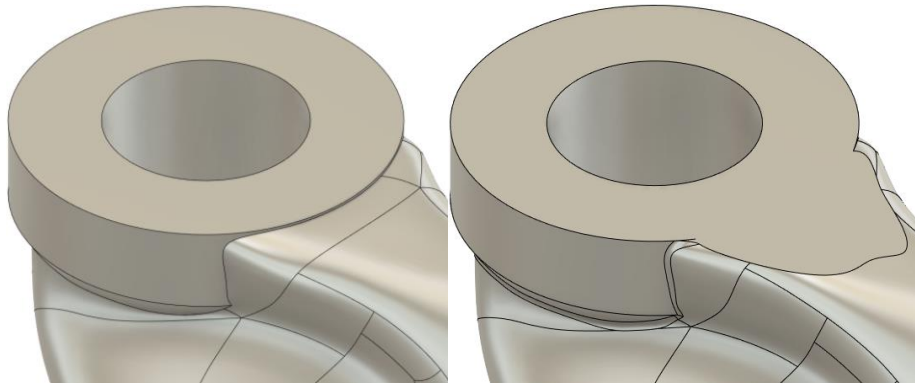
26. Figure Selected raw geometries from the generative studies

Property	Geometry A	Geometry B	Difference [%]
Mass [g]	46,801	52,796	+12,8
Factor of safety	1,75	1,75	0
Maximum global displacement [mm]	0,254	0,228	-10,3

7. Table Properties of the selected raw geometries

As the table shows geometry A compared to geometry B has 12.8% lighter mass but a 10.3% higher maximal displacement. These properties were deemed acceptable for FEM simulation, but extra caution will be needed when examining the displacement values. Geometry B was selected for its low displacement as a safe option.

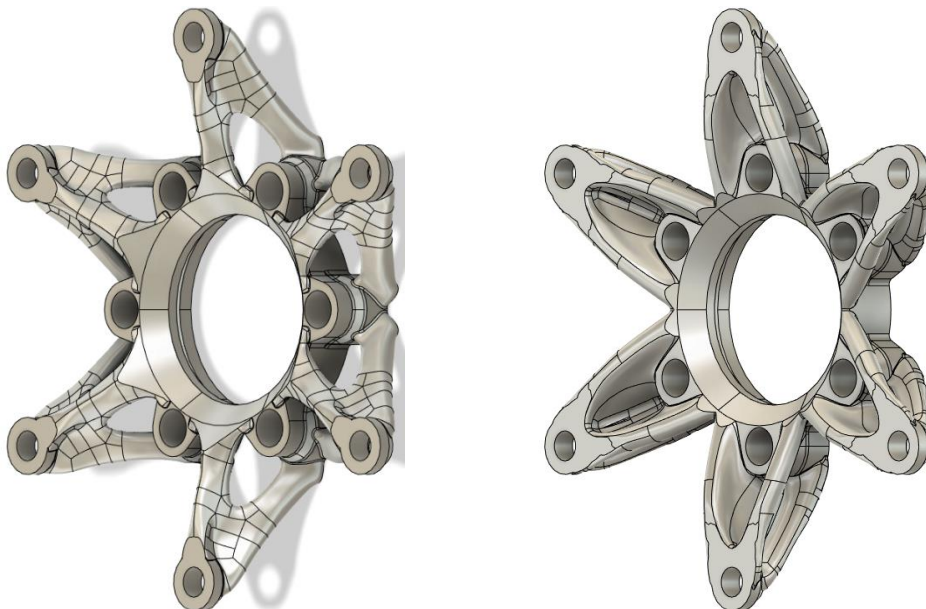
These 1/6 raw geometries are not yet ready for turning them into a full center and FEM simulations. There are small errors and inconsistencies in the material where the generated geometry connects to the preserved geometry. Fortunately Fusion 360 allows the user to edit the raw generative geometry after it was exported from the generative module to its the design module. On both A and B spoke the connections between the generated and the preserved geometry next to mating surfaces of the wheel rim insert and the wheel hub had unnecessary edges. These were removed, thus not only removing potential stress peak points but also increasing the mating surfaces (27. Figure).



27. Figure The center's mating surface to the rim before (left) and after (right)

After the geometries are repaired and improved, they were still asymmetric even though the load cases were symmetrically applied. To fix this the spokes were broken into two halves on their center axis, then the lighter half were mirrored, resulting in a fully symmetric spoke. This not only results the centers being completely balanced, but also greatly simplifies the pre-processes needed before the FEM simulations. This will be further elaborated in the next chapter.

The now symmetric spokes can be turned into full wheel center. This was done in Fusion 360 by using the circular pattern command, then joining the 6 spokes into a single solid body, resulting the following wheel centers (28. Figure).



28. Figure The centers joined together from the 1/6 geometries

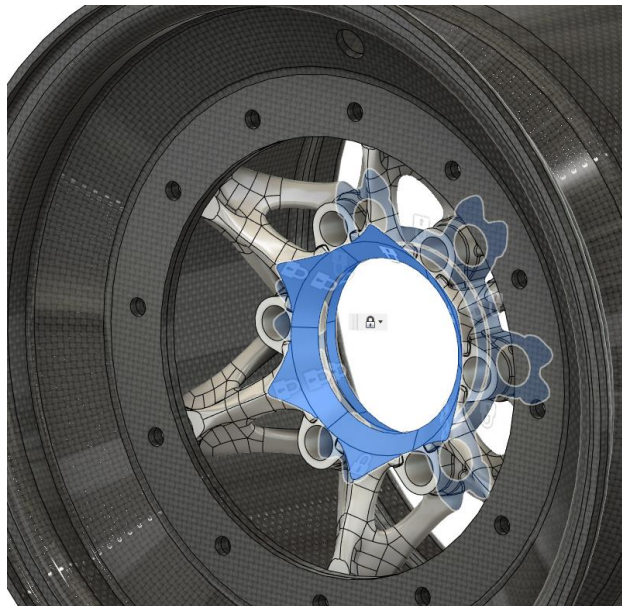
4.4.3. FEM simulation

For the finite element simulation Fusion 360's finite element analysis module was used. This module enables the user to not only perform finite element analyses, but also to make all

the necessary pre-processes on the software's own interface. These include assigning material properties to each component, defining the contacts between components, configuring the constraints and the loads. To verify the results of the Fusion 360 FEM module, they were compared to the results of the same simulation with the same parameters from Ansys Workbench 2020 CAE software. The difference between the mechanical stress values were around 5%, so the Fusion 360 simulation was deemed accurate for this case and for these components.

4.4.3.1. Pre-processes

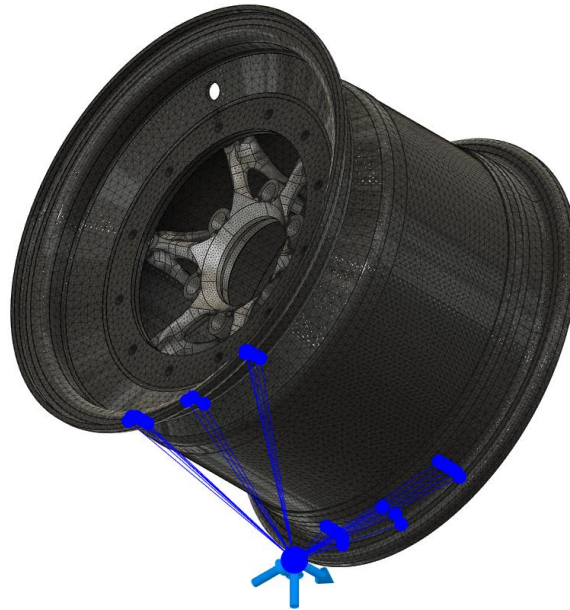
First an assembly was made replicate the full wheel assembly used in real life. This assembly includes the two halves of the CFRP rim and the inserts that go between the wheel center and the wheel rim. All of the components were connected by using the “bonded” contact. This type of component contact does not allow any relative movement between the two connected components. The bolts and nuts were left out intentionally because they complicate and elongate the FEM simulation and their purpose of constraining the other components together was done by the defined component contacts. The tire is also left out, because its simulation is complicated and time consuming and not in the scope of this paper. The materials of each component carried over from the Fusion 360 Material Library used during the design phase, so there was no need to re-configure them.



29. *Figure Structural constraints used during the FEM simulation*

The next step in the pre-processing is the defining of the constraints and the load cases. The constraints are the same used during the generative design pre-process but applied on the whole

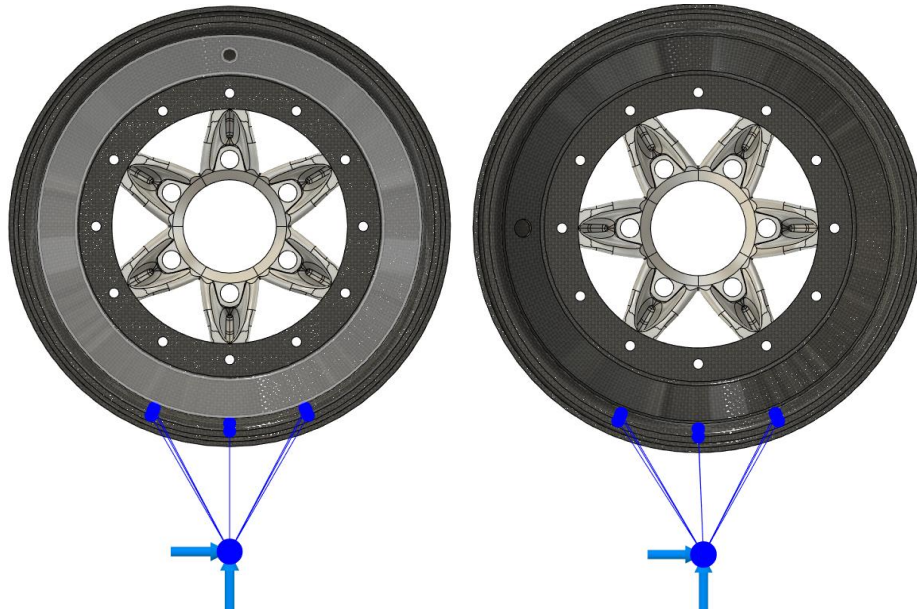
wheel center (29. Figure). The load cases majorly differentiate from the ones used during the generative design process. Instead of acting directly on the center, they are defined as “remote force” acting from the centre point of the contact patch through the bottom 1/8 of the wheel rims’ beading areas (30. Figure). This avoids the need to complicatedly simulate the tire, and also in a way an extra factor of safety, since the tire transmits the forces of the contact patch to the wheel rim on an uncalculated area but estimated larger. The magnitude of the forces acting on the contact patch was clarified in a previous chapter (3. Table).



30. Figure Remote force application to the wheel assembly

One of the most important parts of the FEM simulation is the meshing of the component(s). Unfortunately Fusion 360’s FEA module has less options and configurability when it comes to meshing, than other dedicated FEA software. For the element size 1.75 mm was chosen, as it gives the most accurate result without unnecessarily elongating the computing time. The final count of elements for the assembly was over 520 000.

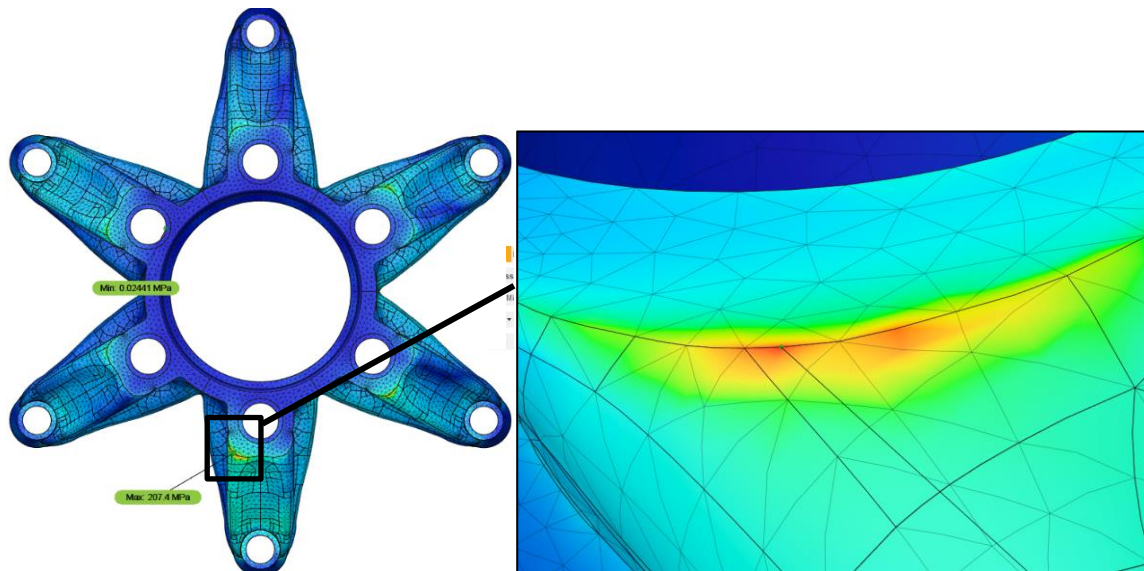
Two simulation scenarios were conducted for each center. The first one is where the vertical force’s axis parallel to the bottom spoke (31. Figure). This is a best-case scenario, since it’s the center’s strongest position, because all of the forces act in the same manner as in the generative design’s load cases, thus they attack the strongest part of the component. The second one is rotated 30 degrees around the Y-axis compared to the first scenario (31. Figure). This is the worst-case scenario. because the weakest spot of the center because forces act the furthest possible way from any spoke.



31. Figure The best-case (left) and the worst-case (right) scenarios used during the FEM simulations

4.4.3.2. Analysing the results

After all of the simulations of the different scenarios has finished, the results can be analysed. First Geometry A's mechanical stress values were comprehended. The higher stress values, nit as expected, were reached on the best-case scenario, so that will be presented in this part of the chapter. On the result screen (33. Figure and 34. Figure) with dark blue are shown the lowest values and with bright red the highest values.



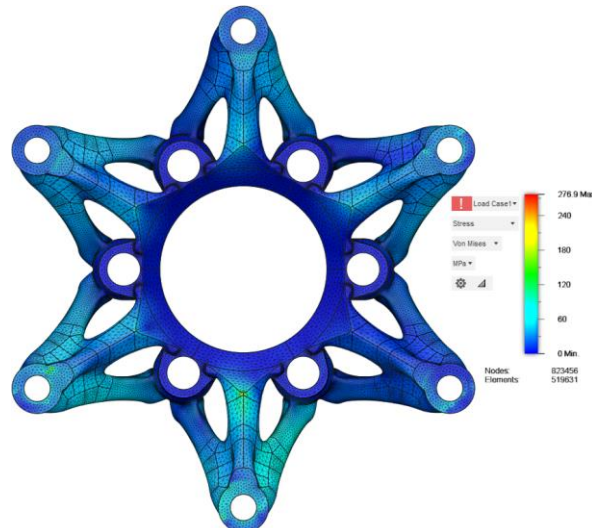
32. Figure Stress peaks next to the constrained surface

As can be seen on the highlighted figure (32. Figure) the peak values are concentrating on a small area of the edge of the mating surface of the center and the wheel hub. These are stress peaks, occurring around distorted elements or next to edges of constrained areas. They can be

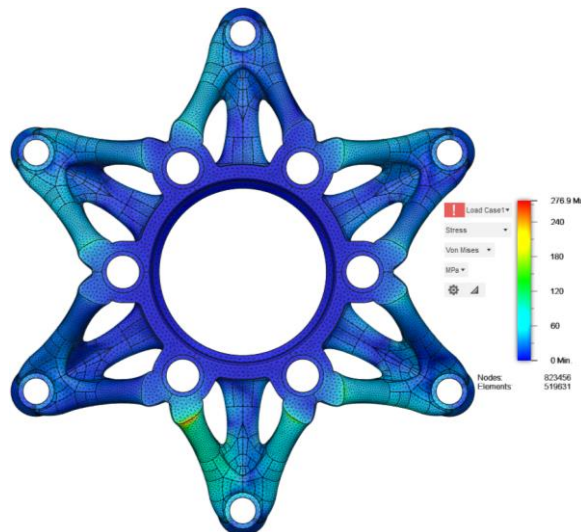
recognized by a high stress value only occurring around a single element and the value quickly dropping in the neighbouring elements. These peak values can be ignored when evaluating the results but shouldn't be forgotten about. The highest stress values, not counting the peaks, is 212 MPa, under the 240 MPa Yield strength, given by the material's manufacturer. Other than the aforementioned stress peaks, the distribution of the mechanical stress is acceptable.

The place of maximum displacement (35. Figure) as expected is on the end of the spoke, at its furthest point. Its value of 0,122 mm is within the acceptable range of distortion.

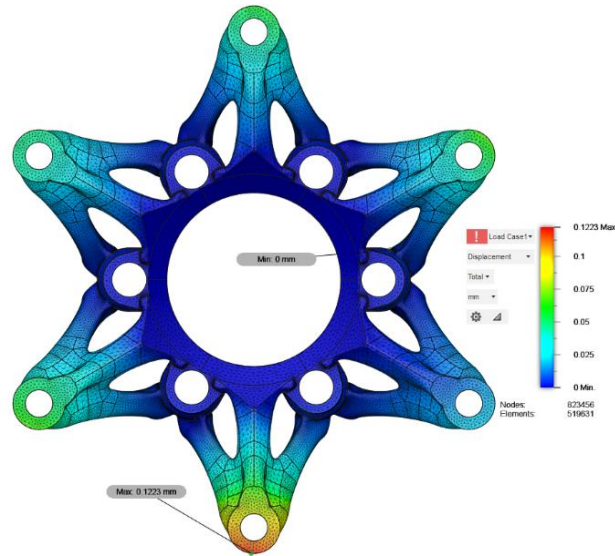
The worst-case scenario was evaluated as well. The maximum of the mechanical stress was lower than in the other scenario, at 204 MPa, but the displacement was slightly higher at 0,127 mm. Both the scenarios were tested with the forces that were validated to act at the time. In this case the highest mechanical stress value was under well under the yield strength, even with counting the stress peaks. The displacement was under 0.1 mm.



33. Figure Distribution of mechanical stress on the outside of the center A



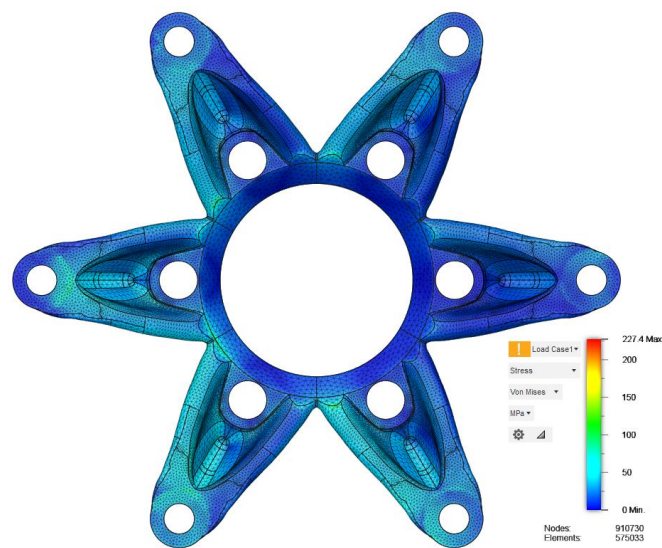
34. Figure Distribution of mechanical stress on the inside of the center A



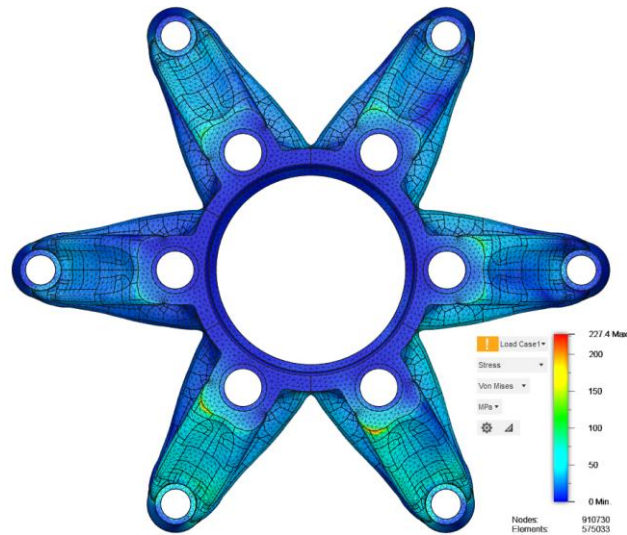
35. Figure Displacement view of center A

For Geometry B's evaluation, the worst-case scenario was chosen. Geometry B produced excellent results, both in mechanical stress and in displacement, during the best-case scenario, better than Geometry A and even better than last year's design, while being lighter and having a higher ET value. Similar mechanical stress peaks appeared on the results of Geometry B's simulations, as previously. These won't be taken into account as well, for the same reasons as previously. The highest mechanical stress value was 201 MPa and it was located around the constrained surface. The stress distribution around the center (36. Figure and 37. Figure) was excellent with no outstandingly stressed areas.

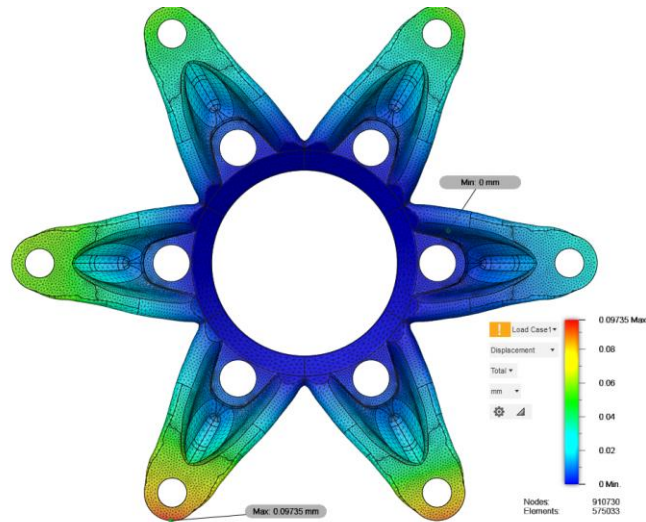
During the worst-case scenario the displacement value only reached 0,097 mm, at the very end of the spoke (38. Figure), same as in Geometry A's simulation.



36. Figure Distribution of mechanical stress on the outside of the center B



37. Figure Distribution of mechanical stress on the inside of the center B

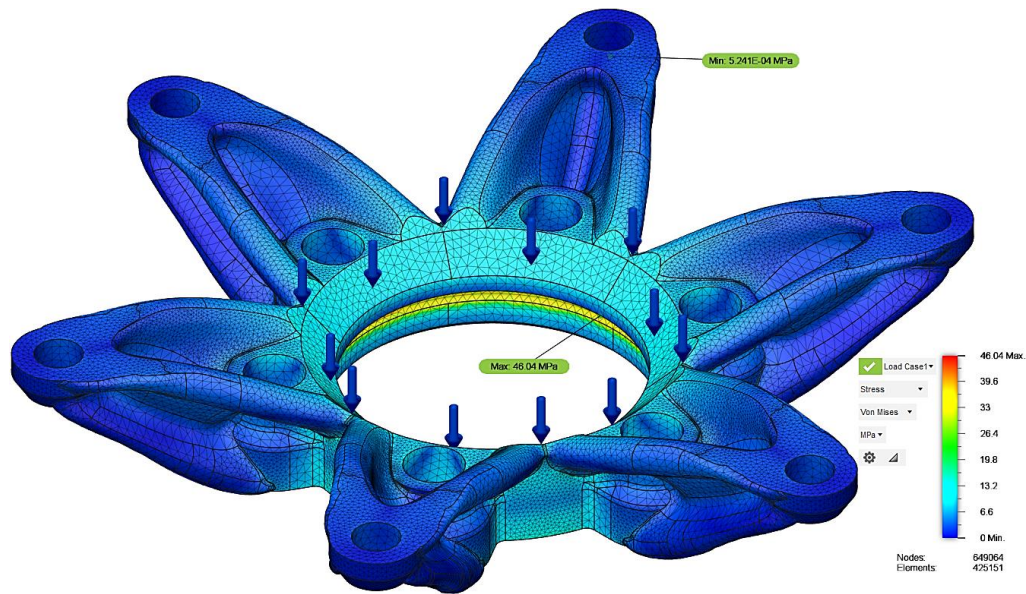


38. Figure Displacement view of center B

The previously validated, at the same time acting forces were applied to Geometry B's simulation as well, both in best-case and in worst-case scenario. The highest mechanical stress value was 138 MPa and highest was 0,067 mm.

4.4.3.3. Clamping force simulation

The previously mentioned effects of clamping force on the centers mating surface were simulated on both center designs. For these simulation Fusion 360 was used as well. This is a quite simple simulation compared to the previous ones. Instead of an assembly only the centers were simulated. The constrained surfaces were the same, with the exception of the conical mating surface of the centerlock wheel nut. The load case was a single force acting along the Y axis on the aforementioned centerlock mating surface, as shown previously (16. Figure). The magnitude of the force was calculated in a previous chapter.



39. Figure Stress distribution in the clamping force simulation

First the simulation of Center B is presented. The maximal value of the mechanical stress was located in the groove between the mating surfaces of the centerlock and the wheel hub, and its value was 46 MPa. The stress is evenly distributed around the center, with no peaks or outstandingly highly stressed areas. The dislocation's highest value is 0,003 mm and located in the aforementioned groove. Center A's values differ minimally from Center B's, so they won't be presented separately.

Both the mechanical stress and the dislocation values are well within the acceptable range, so both centers' centerlock wheel nut can be safely torqued down to 200 Nm.

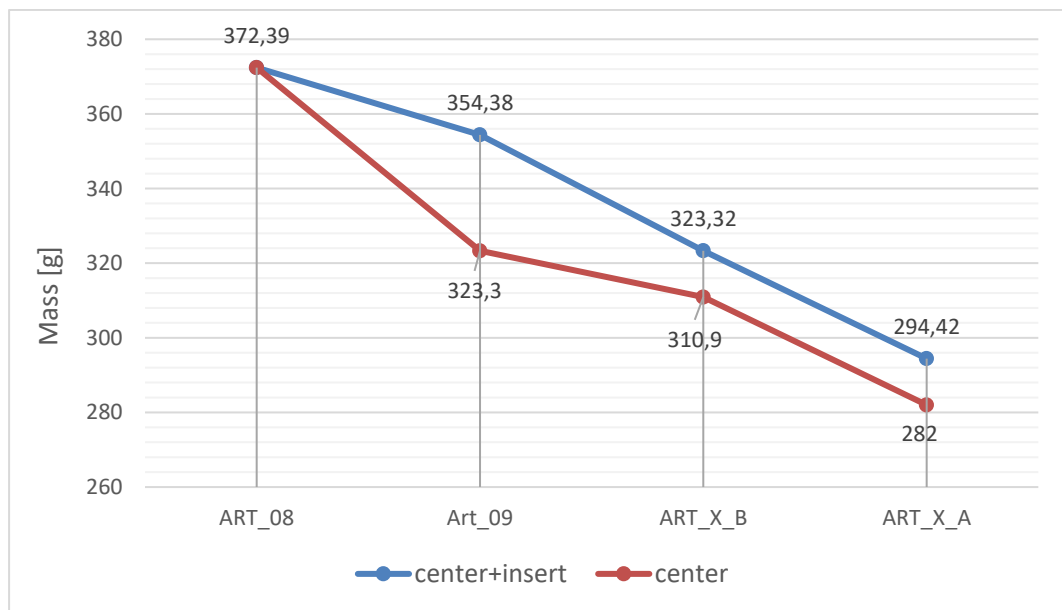
4.4.4. Comparison

To make the decision between Center A and Center B the following comparison table was made (8. Table). It compares the geometries' mass, factor of safety, peak stress values and their displacements. It also includes the center used during the previous season, to better highlight the advancements made with the new designs. All the simulated values were simulated with the same load cases.

	ART_09 Rear Center	Center A	Center B
Mass [g]	323,3	282,0	310,9
Factor of safety	1,151	1,132	1,192
Maximum stress [MPa]	208,5	212,1	201,3
Maximum displacement [mm]	0,1149	0,127	0,097

8. Table Comparison between the simulated values of the wheel center designs

The table makes it very clear that Center B has superior qualities, compared to the other centers, with the exception of its weight. While it saves more than 13 g on each center, its more than 10% or 28 grams heavier than Center A. Center A's only upside compared to the other two designs is its lower weight. When examined while using load case, that replicates the actually at the same time acting forces, Center B has the highest safety factor, while also having the smallest displacement value.



9. Table The weight difference between the center design

When comparing these results, it is clear that Center B is the better choice to be realised. It has better physical attributes, and has a higher factor of safety, especially compared to Center A. This makes it a safe option while still achieving weight reduction, even more so when the weight of the inserts is also calculated into the weight of the centers (9. Table). This is possible, thanks the enlarged ET value of the center, which allows the use of the smaller center insert, the same ones used in the front wheel assembly (12. Figure).

4.5. Machined design

Then the machined centers have to be designed. In case one of the teams machining partners has free manufacturing capacity sooner than expected, they have to be ready in time with all their necessary documentation.

Machined wheel centers aren't new territory for the team, so instead of focusing on learning the basics, the design can be the centre of attention. Also last season's topologically

optimised center helps to understand and to design a lighter and better center.

4.5.1. Material selection

For the machined centers' material, their mechanical properties (such as tensile strength, yield strength, elasticity, etc. (10. Table)), costs, manufacturability (how difficult and expensive to produce the centers from them), knowledge in the team already about them and their current availability in retail are taken into consideration. A decision matrix was made to illustrate these different decisional factors (11. Table). In the matrix the lowest rating is 6, while the best is 1.

	Density [kg/m ³]	Tensile strength [MPa]	Yield strength [MPa]	Modulus of elasticity [GPa]	Poisson ratio [-]
Aluminium 6061	2700	310	275	69	0,33
Aluminium 7075-T651	2810	572	503	72	0,33
Steel S355	7850	470	355	190	0,3
Stainless Steel AISI304	8000	505	215	195	0,29
Magnesium AY80A-T5	1800	345	250	45	0,35
Titanium 6Al-4V	4430	1030	880	113	0,35

10. Table Mechanical properties of the potential base materials

Factors	Aluminium 6061	Aluminium 7075-T651	Steel S355	Stainless Steel AISI304	Magnesium AZ80A-T5	Titanium 6Al-4V
Mechanical properties	4	2	6	5	3	1
Potential weight	4	3	5	5	2	1
Price	3	4	2	1	5	6
Manufacturability	1	1	2	3	5	4
Possessed knowledge	1	1	2	2	4	3
Availability	3	4	1	2	6	5
Sum	16	15	18	18	25	20

11. Table Decision matrix used to select the material of the wheel machined centers

As the matrix shows, the most advantageous material to use for the machined centers is Aluminium 7075-T651. It combines good mechanical properties with ease in manufacture. It is also readily available commercially, but at a higher price than other, lesser aluminium alloys. Another advantage is the team's high familiarity with this material since many suspension

components are machined out of this material.

Aluminium 6061 is a weaker alloy compared to Aluminium 7075, but can be used in less critical areas, such as non-weight bearing brackets. Unfortunately it isn't true for the wheel centers.

Steel S355 and Stainless Steel AISi304 are both strong material that are easily available. The components made out of them are heavier than ones made out of the other materials.

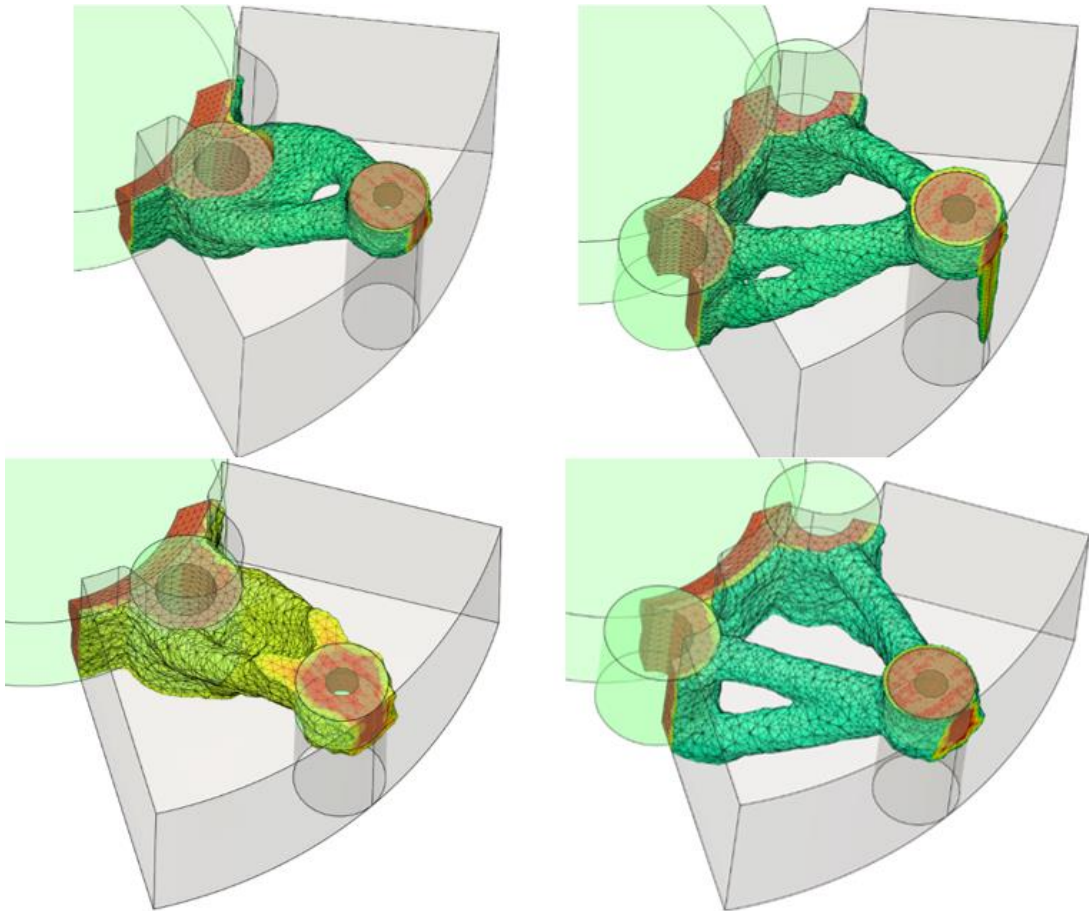
Components made out of Magnesium AZ80A-T5 are exceptionally light. The strength of Magnesium is similar to Aluminium 6061, but its density is the 2/3 of Aluminium 6061's. Its main drawbacks are its high price and its difficult forming.

As further explained in the 3D printed centers material selection, Ti6Al-4V is an excellent material for applications where low weight is critical, but at a considerably higher cost than other materials. In this application, where machinability is important, titanium alloys other drawback comes to light. To machine Ti6Al-4V special machining tools and material specific techniques are required, making it more costly than machining aluminium or steel.

4.5.2. Design

As where with the 3D printed center's design, the machined one's process begins with the reduced geometry. These aren't the same ones used in the previous chapter, since these designs will incorporate the geometries of the inserts used in 3D printed centers.

To better understand the optimal geometries for each center layout, Fusion 360's topological optimisation module was used. This module works similarly to the generative module used in the previous chapters, but instead connecting bodies, to form an optimal shape, it removes the unnecessary parts from a larger body. Using the same load cases as in the generative studies, the topological optimisation process resulted the following (40. Figure) geometries.



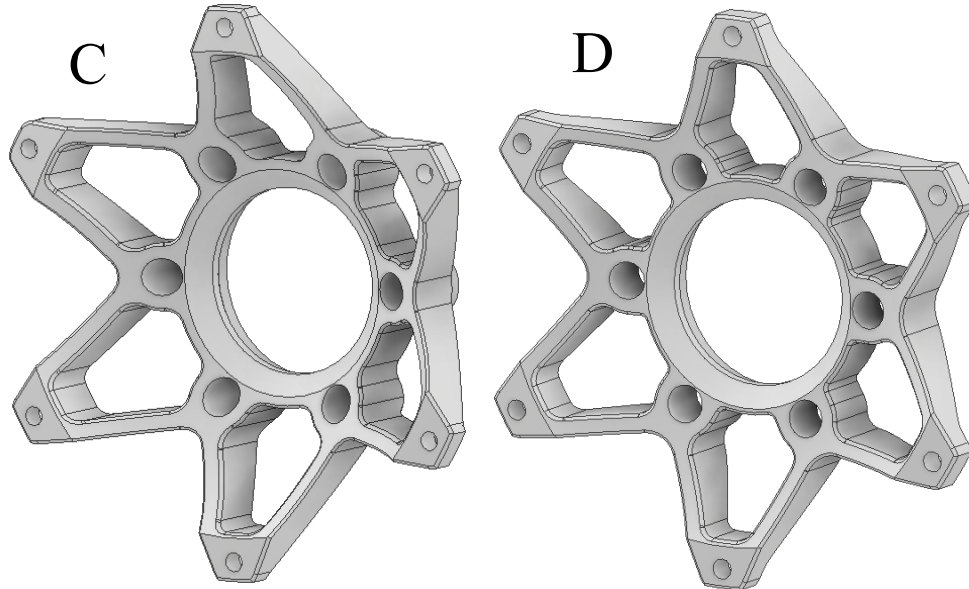
40. Figure Topologically optimised wheel center layouts

The generative module was tested for the machined center designs as well. The generative module of Fusion 360 not only supports optimisation for additive manufacturing, but for 3- and 5-axis milling too. Unfortunately this machinable designs (41. Figure) have quite complicated geometries, for which would hard or impossible to find a manufacturing partner.



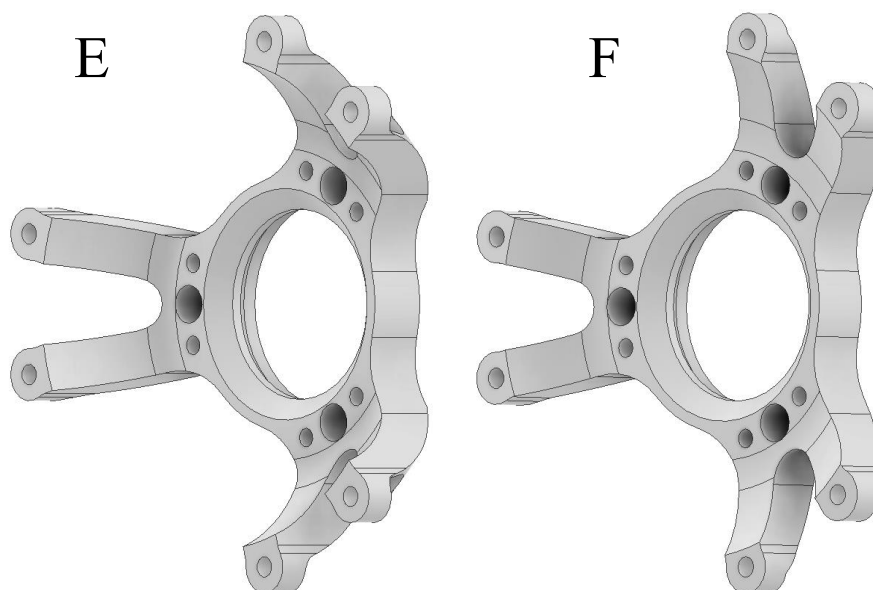
41. Figure Different machinable center geometries made with generative design

Because the geometries produced by these modules were unusable for this purpose, the final center geometries are made manually in Autodesk Inventor CAD software. First a set of centers (42. Figure) were made based on the shapes produced by the topological optimisations. These centers are marked as Center C in the front axis and Center D in the rear.



42. Figure Front (left) and rear centers based on the topological optimisations

An alternative set of centers (43. Figure) were made as well. These weren't based on the topological optimisations or the generative results. Instead they were inspired by a competition analysis focusing on multi-piece CFRP wheels used in Formula Student. Instead of the 6-bolt, 6-spoke pattern used so far in this thesis, they use a 6-bolt 3-spoke pattern. This symmetry allowed the use of three pin holes instead of six, thus reducing the weight. These centers are marked as Center E in the front axis and Center F in the rear.

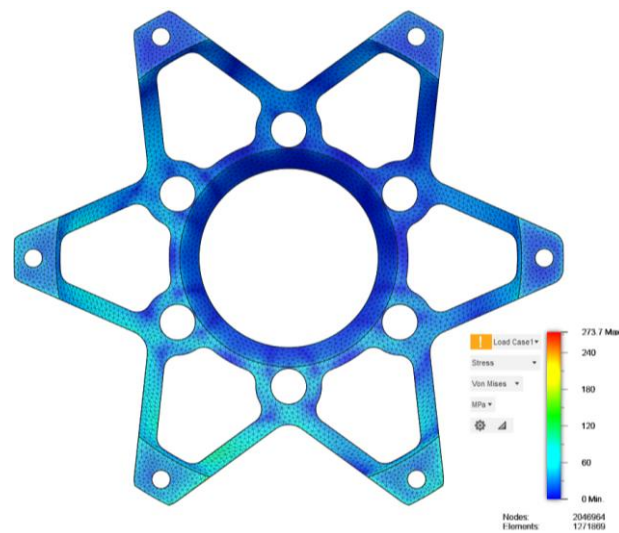


43. Figure Front (left) and rear centers based on the competition analysis

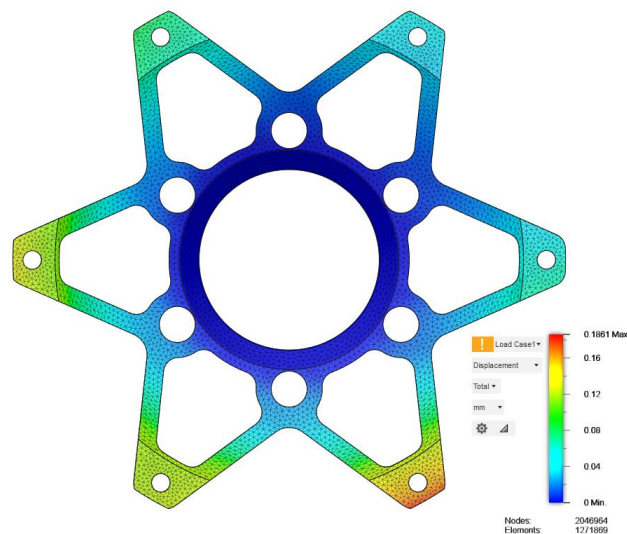
4.5.3. FEM simulation

The FEM simulations for the machined centers followed the same route as for the additively manufacturable centers. Because of this the pre-processes won't be presented again since they are identical.

First the Centers, C and D are examined. For both the worst-case scenario was chosen for examination. Both Geometry produced excellent results in mechanical stress and in displacement. Similar mechanical stress peaks appeared on the results of the simulations, as previously. These won't be taken into account as well, for the same reasons as previously. The highest mechanical stress value in Center C was 192.5 MPa (44. Figure), in Center D it was 187.8 MPa. The stress distribution around the centers were excellent with no outstandingly stressed areas.

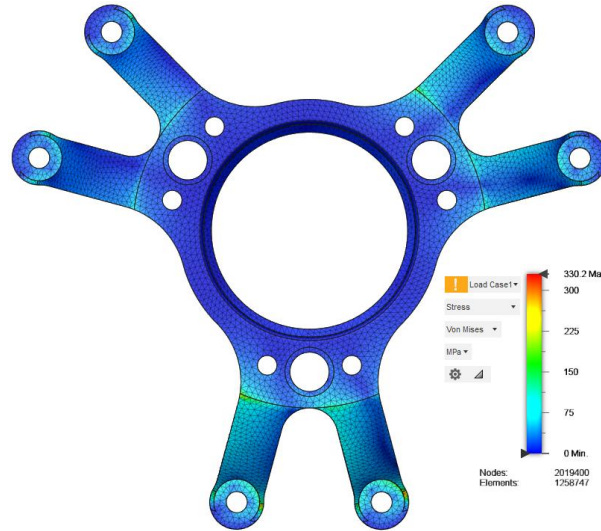


44. Figure Distribution of mechanical stress in Center C

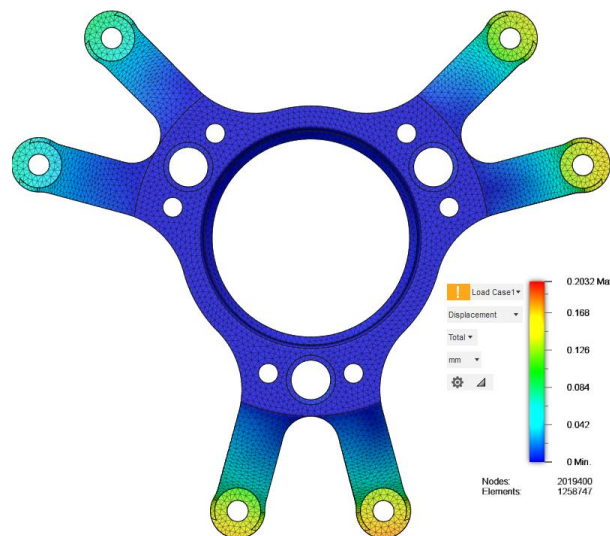


45. Figure Displacement view of Center C

Then Center E and F were tested, both in the best-case scenario. They produced worse mechanical stress values as the previous set of centers with 330 MPa (46. Figure) and 320 MPa respectively. The displacement of Center E was 0.203 mm (47. Figure), which is slightly over the designated limit, while Center F with 0,172 mm was within it.

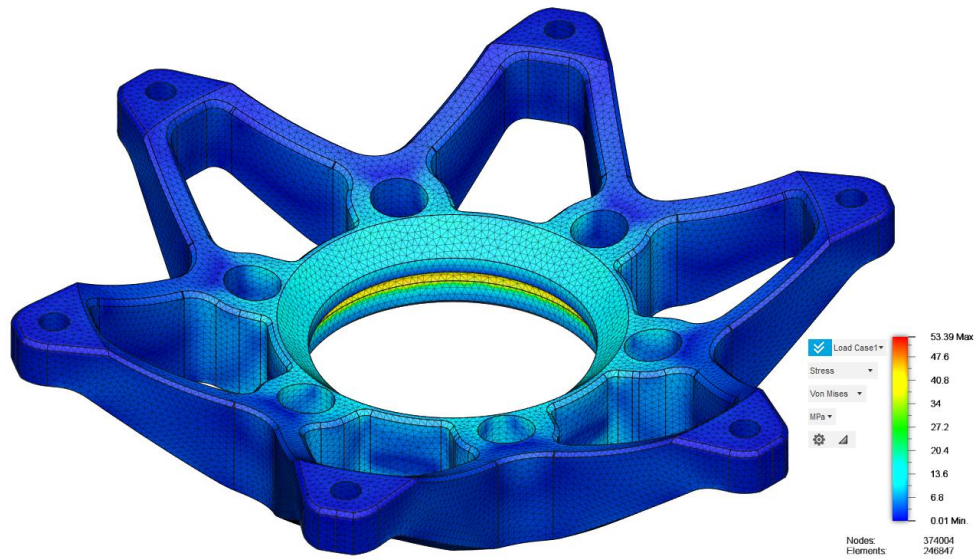


46. Figure Distribution of mechanical stress in Center E



47. Figure Displacement view of Center E

Lastly the clamping force simulations were conducted. First the simulation of Center D is presented. The maximal value of the mechanical stress was located in the groove between the mating surfaces of the centerlock and the wheel hub, and its value was 53,4 MPa. The stress is evenly distributed around the center, with no peaks or outstandingly highly stressed areas. The dislocation's highest value is 0,004 mm and located in the aforementioned groove. The other centers' values differ minimally from Center D's, so they won't be presented separately.



48. Figure Stress distribution in the clamping force simulation

Both the mechanical stress and the dislocation values are well within the acceptable range, so all centers' centerlock wheel nut can be safely torqued down to 200 Nm.

4.5.4. Manufacturability

After consultation with ART members with extensive CAM knowledge both sets of centers were deemed manufacturable with 3-axis CNC mills. To test the manufacturability of the centers with a 3-axis CNC mill, a test program was made using Fusion 360 CAM module. The use of 5-axis machines could speed up the process in certain areas, but it isn't necessary.

4.5.5. Comparison

To make the decision between Center C and E the following comparison table was made (12. Table). It compares the geometries' mass, factor of safety, peak stress values and their displacements. It also includes the center used during the previous season, to better highlight the advancements made with the new designs. All the simulated values were simulated with the same load cases.

	ART_09 Front Center	Center C	Center E
Mass [g]	337,5	359,6	362,2
Factor of safety	1,29	2,59	1,52
Maximum stress [MPa]	186	192,5	330
Maximum displacement [mm]	0,142	0,186	0,203

12. Table Comparison of the centers of the front axis

The table makes it very clear that Center C has superior qualities, compared to Center E. It is 6,5% or 22,1 grams heavier than Center used in ART_09. Center E's has inferior qualities and its displacement exceed the given limit of 0.2 mm. Because of this Center C is chosen for manufacturing for the front axle, in case the additively made centers cannot be manufactured.

Next is the comparison of the centers for the rear axle. As with the previous cases a table was made (13. Table) to make the choice between the centers more transparent. It compares the geometries' mass, factor of safety, peak stress values and their displacements. It also includes the center used during the previous season. All the simulated values were simulated with the same load cases.

	ART_09 Rear Center	Center D	Center F
Mass [g]	323,3	330,3	329,6
Factor of safety	1,151	2,65	1,56
Maximum stress [MPa]	208,5	187,8	320
Maximum displacement [mm]	0,115	0,173	0,172

13. Table Comparison of the centers of the rear axis

The table makes it clear that Center D is the better choice. It has better qualities with the exception of weight, which is only 1 gram heavier than Center F's. Its weight is also only 2,1 % larger than the previous season's center. For these reasons Center D will be used if the additively made centers cannot be manufactured.

5. Possible future improvements

To design better wheel centers in the future, first better and more information about the loads of the wheel is needed. A great tool for this the previously mentioned strain gauges. When their data recording device is repaired, it could provide information, after proper validation, on the forces that actually occur in the suspension during different situations.

Another great option to improve the design is the use of a dedicated FEA software. Fusion 360 is a great option for simpler FEM simulations, such were the simulation of the clamping force, but for more complicated simulations using assemblies instead of a single component, its accuracy is questionable and harder to validate. A FEA software, especially when used together with a dedicated pre-processor software, allow much better control over the properties of the mesh, resulting better mesh quality and thus more accurate results. This way the mechanical stress peaks could be eliminated or at least reduced in size and magnitude.

For future designs, it could be beneficial to look into designing the wheel centers along the wheel rims and the wheel hub. This way each component would be optimally designed to work together and wouldn't have to make design compromises for the sake of compatibility. For example, if the wheel rims size is configured such way that the wheel centers mating surface would be on the same plane as its mating surface to the wheel hub, thus minimalizing the ET value, the center could be made considerably lighter and cheaper.

A more time and cost intensive possible improvement is the development of a single piece CFRP wheel. This type of design could drastically reduce the weight of the wheel assembly, by eliminating the need for fasteners, and by replacing every aluminium part with carbon fibre. To properly design this type of wheel deep understanding of composites materials and the forces of the suspension is needed. They would be also quite expensive, not only because of the price of the raw CFRP, but because of the complicated laminating mold needed to manufacture them.

6. Conclusion

In conclusion the new wheel center designs achieve on their main goal, by improving every aspect of the wheel center used in the previous season. The 3D printed center is lighter and stiffer than the previous design while incorporates last season's ET change. The set of machinable centers provide the team an excellent alternative in case the team's additive manufacturing partner can't make two sets 3D printed centers. During the design members of Arrabona Racing Team gained deeper knowledge in the use of generative design and in additively manufacturable components.

Some of the other design goals set at the beginning of the design phase were not met. The planned minimum factor of safety was 1,2 and the final 3D printed center design's safety factor is 1,192, which is close but technically does not meet the requirement. The wheel center was still deemed acceptable because the forces used in the FEM simulation couldn't possibly occur at the same time in real life, thus the center is safe to use in race conditions. When simulated with the forces that could occur at the same time in a real scenario the center has a far greater safety of factor than 1,2. Another design goal was, 10% weight savings compared to last year's design, but the new design's actual weight saving was only 8,8%. This is still a significant weight saved in the unsprung and rotating mass of the car, which will improve the handling and the fuel efficiency. All of the other design criteria of the 3D printed center were met. The machined centers hit all of their design goals, especially their mass. The original goal was that each center can't be more than 20% heavier than its corresponding 3D printed center, and in the end the front center weighs only 7 % more, while the rear is 6 % heavier.

The purpose of this thesis was not only to present the design process of the wheel centers of a Formula Student Race car, but to give future Arrabona Racing Team members a blueprint of how to design generatively designed and lightweight metal components, and to ensure the continuation of the current success of the team.

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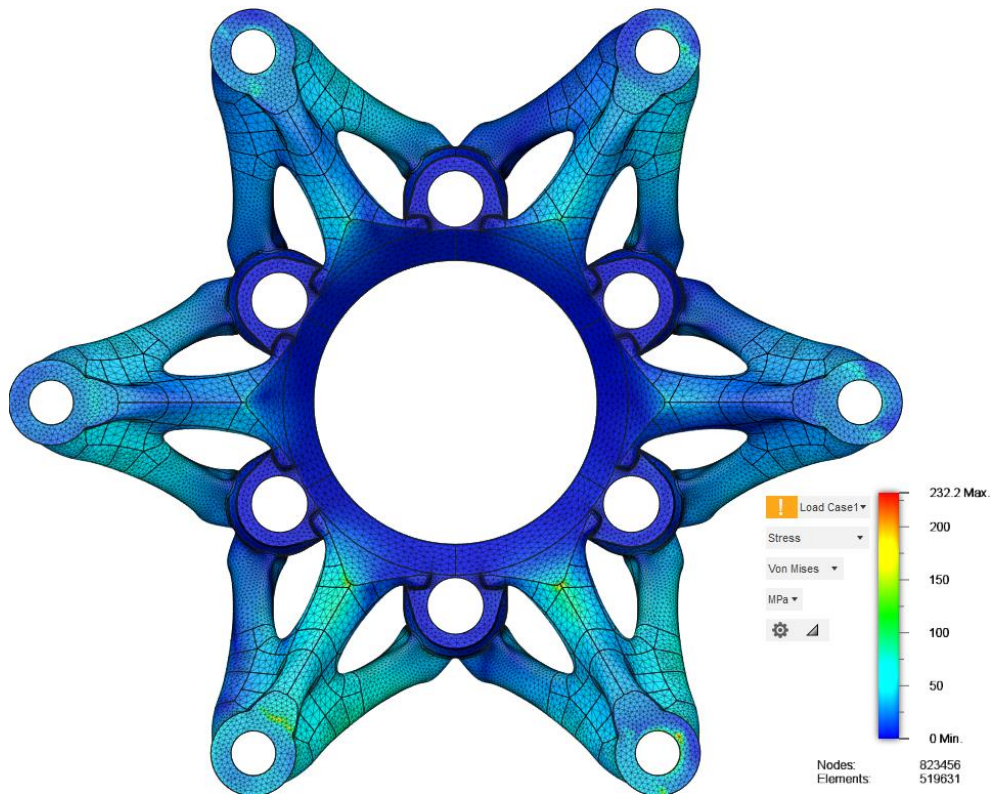
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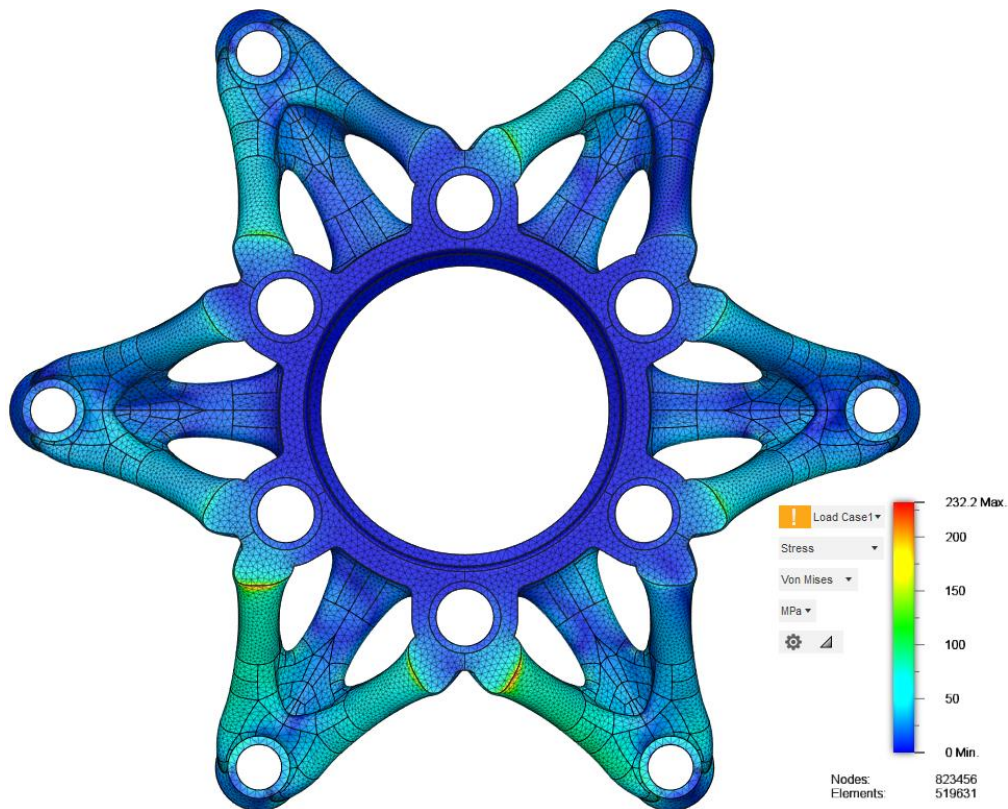
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8. Annexes

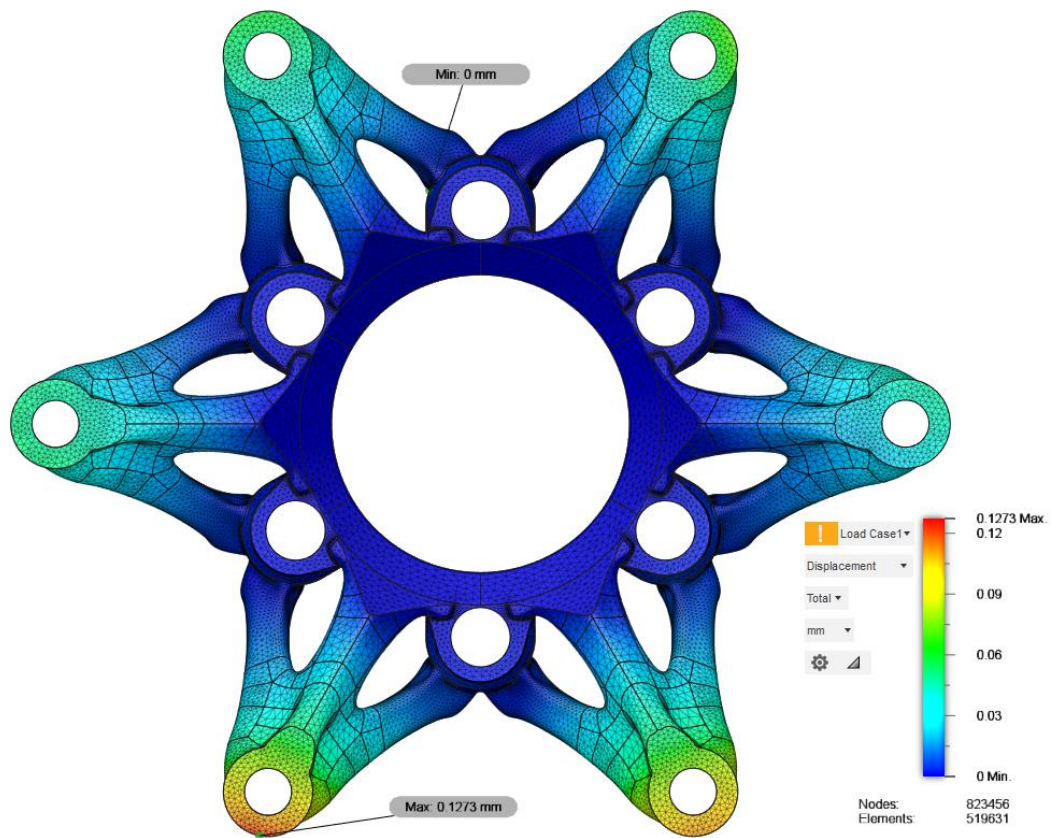
Annex 1: Distribution of mechanical stress on the outside of the center A



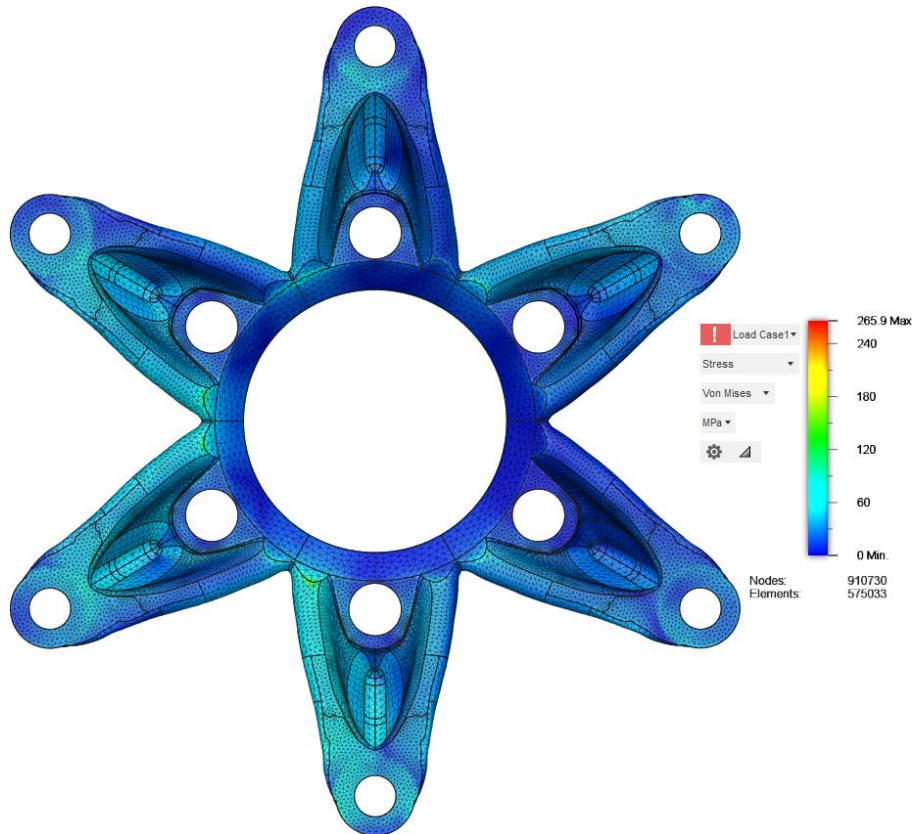
Annex 2: Distribution of mechanical stress on the inside of the center A



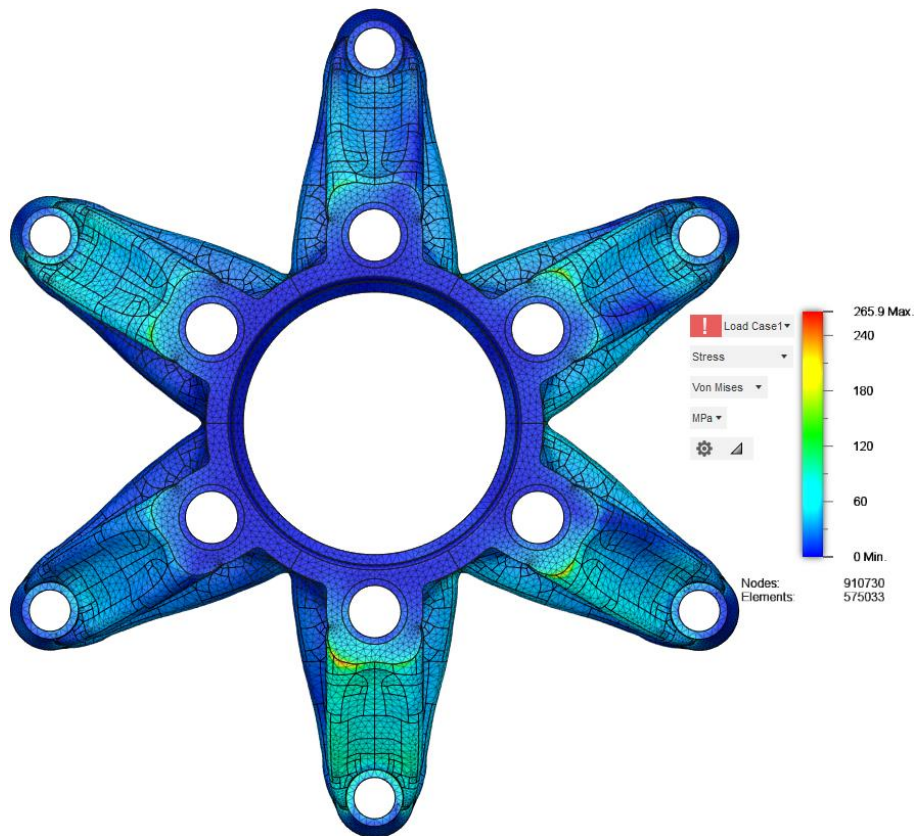
Annex 3: Displacement view of center A



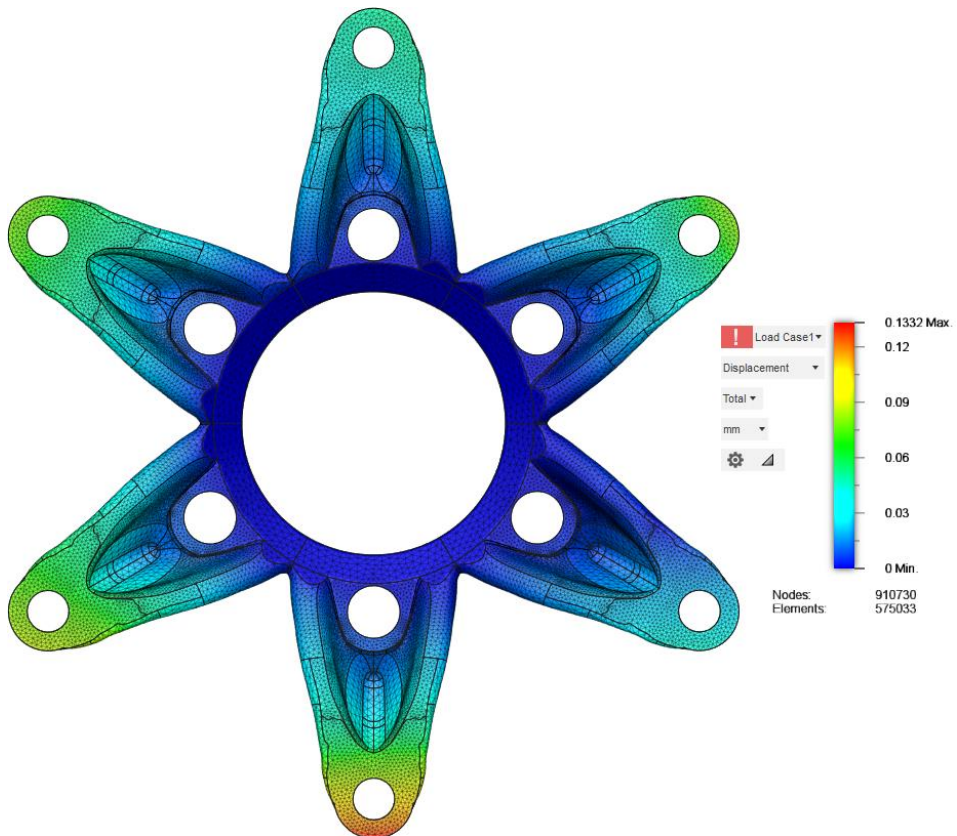
Annex 4: Distribution of mechanical stress on the outside of the center B



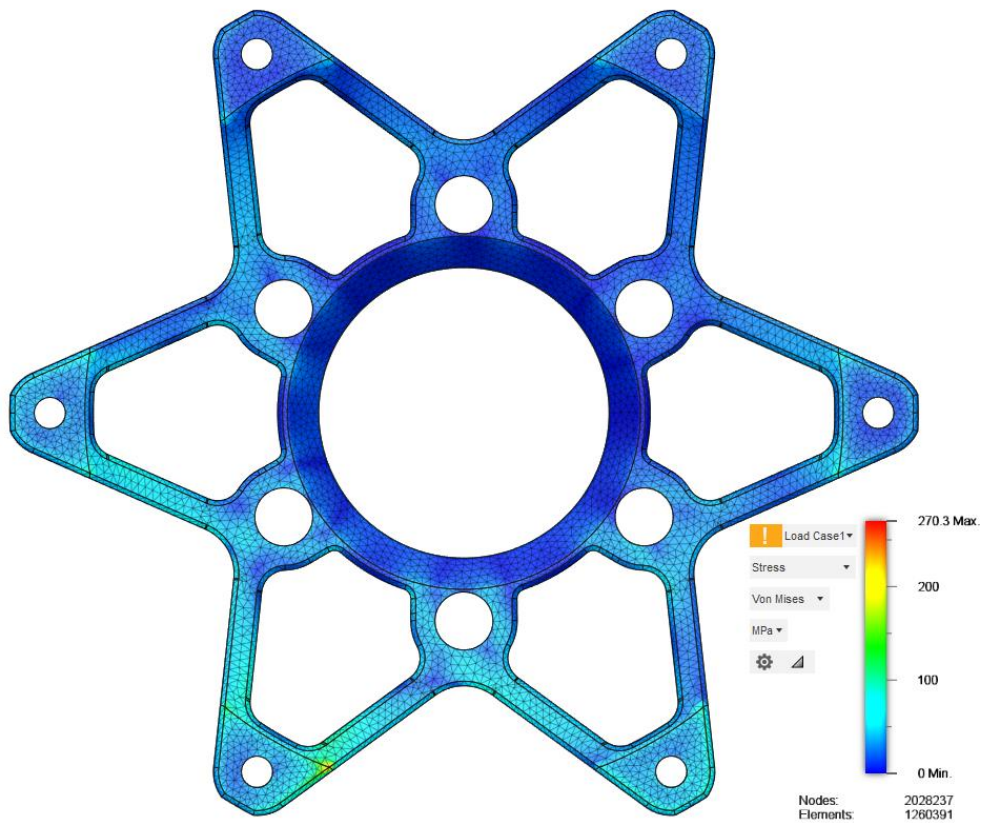
Annex 5: Distribution of mechanical stress on the inside of the center B



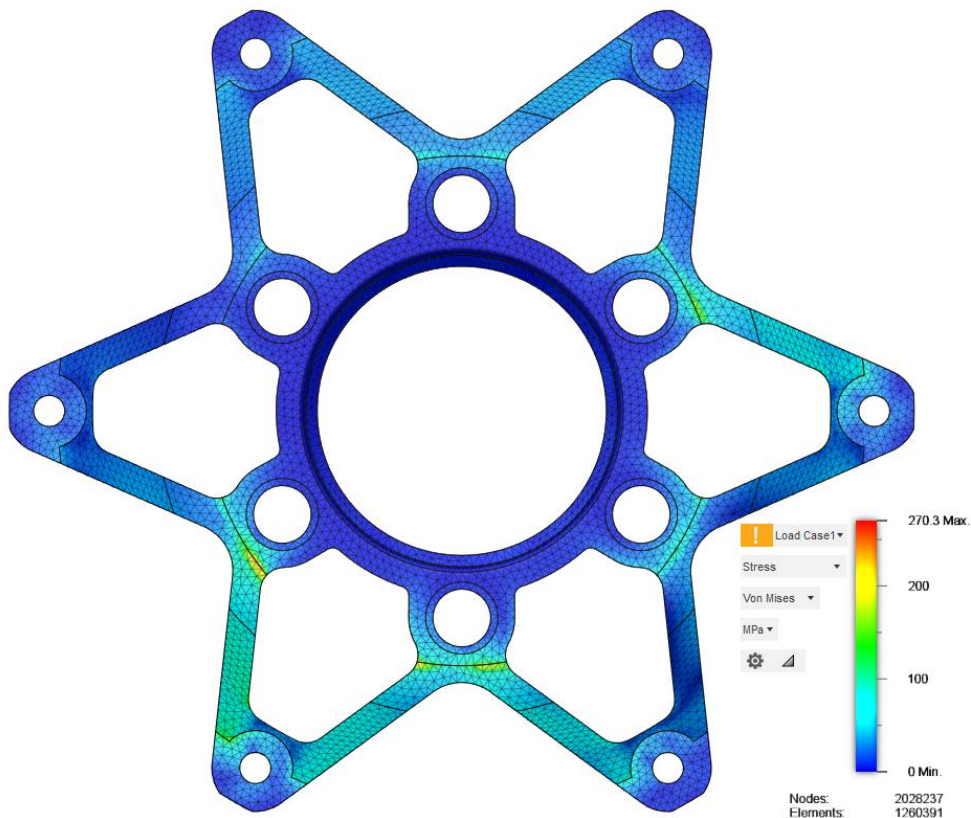
Annex 6: Displacement view of center B



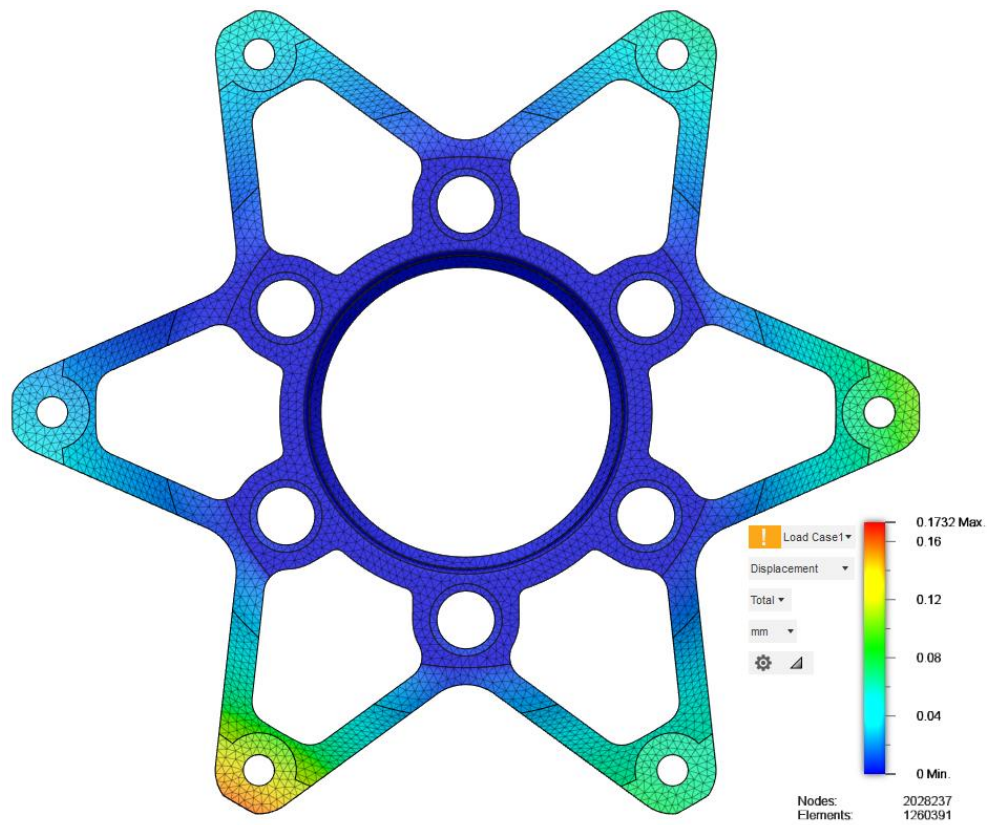
Annex 7: Distribution of mechanical stress on the outside of the center D



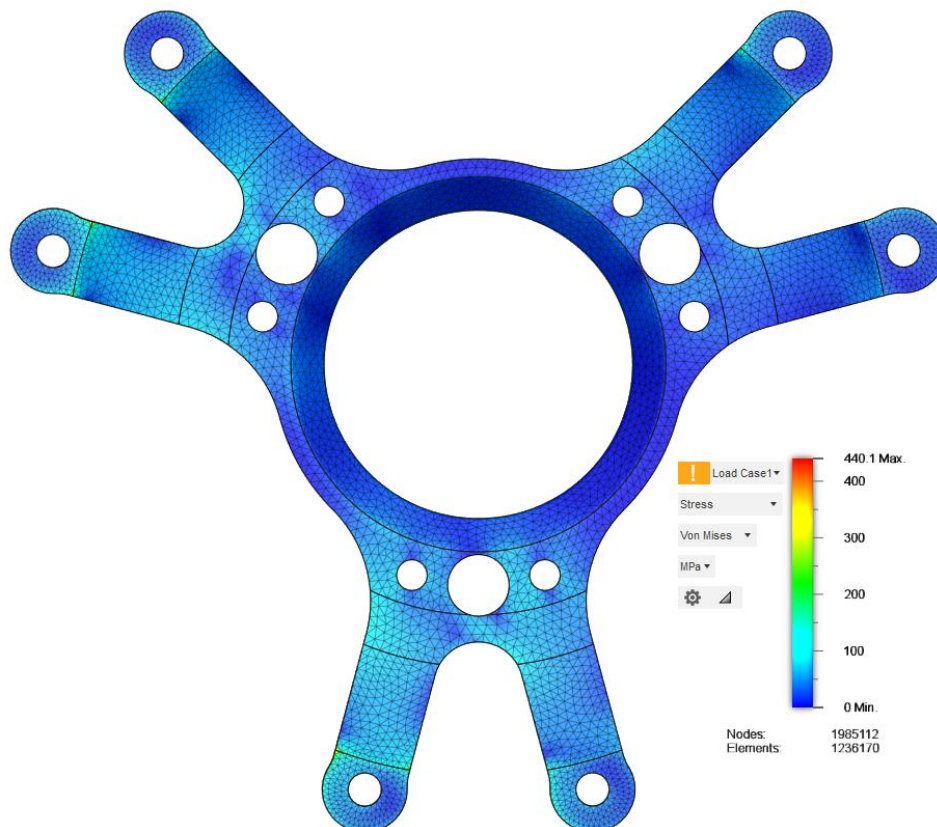
Annex 8: Distribution of mechanical stress on the inside of the center D



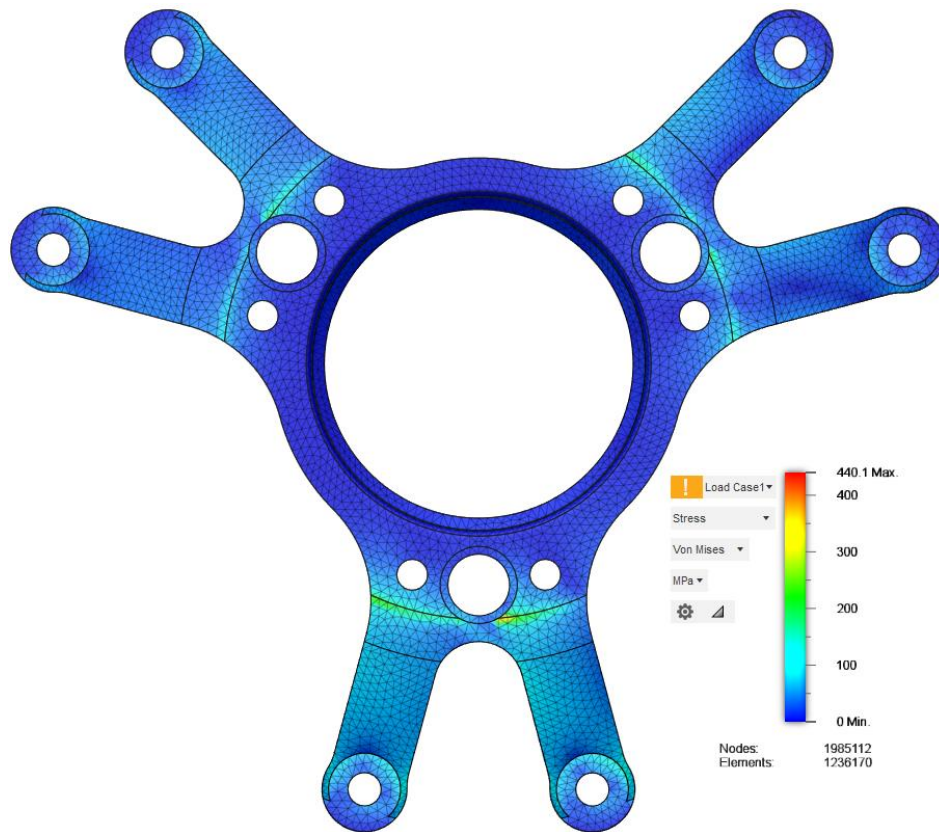
Annex 9: Displacement view of center D



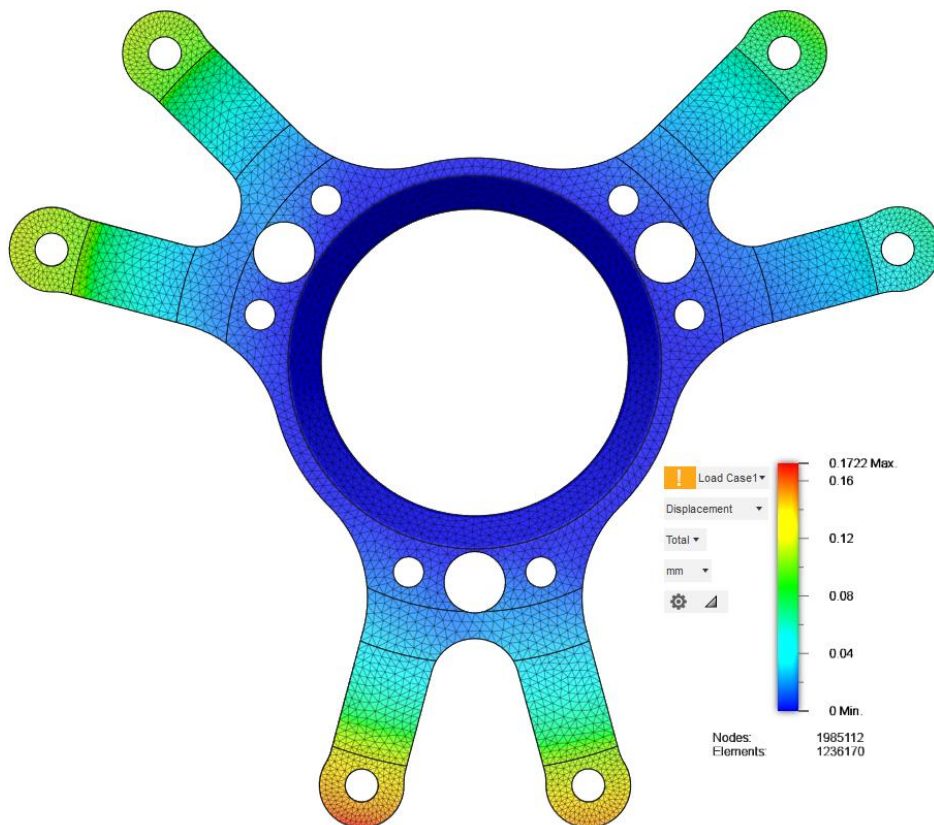
Annex 10: Distribution of mechanical stress on the outside of the center F



Annex 11: Distribution of mechanical stress on the inside of the center F



Annex 12: Displacement view of center F



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