Mass Reduction of Upright of a Racing Car with Innovative Methods

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This article deals with the team's examination of a suspension component of their Formula race car, the upright, using various development methods. The original component was made of 6061 aluminum alloy and weighed 530 grams. In addition to weight reduction, we examined the resistance and structural strength optimization of the upright using various methods. The redesigns were done using FUSION 360 and ANSYS programs." The vehicle's performance characteristics are influenced by the material, the load capacity. To ensure competitiveness, several studies and publications have been carried out in terms of compliance with mass and fatigue strength criteria.

Keywords: generative design; topology optimization; shape optimization; mass reduction; Formula Student; upright; suspension development

1 Introduction

The tasks of the upright include transmitting the forces between the road and the vehicle, thus creating sufficient grip. Another task is to reduce the dynamic stresses of the vehicle's components, increasing their life cycle. It is important for the system to operate in the appropriate vibration range, thus avoiding self-excitation phenomenon and ensuring comfortable traveling for passengers. A well assembled suspension can actively contribute to the car's driving stability.

Taking into consideration the competition regulations, the O.U.R. Team has built a double-wishbone suspension, which is easy to install and provides very wide adjustment options. This construction consists of a lower and an upper control arm pair (so-called A-Arm), and another two - one is responsible for suspension and one for steering. On the non-steered rear axis, the steering bar is replaced by a fixed bar [Figure 1]. The bars are connected to the upright at three different points, using different ball joints. The upright is the part of the suspension where the components are mounted. The wheel shaft is fixed with a double bearing center of the upright. On the outer side, the wheel rim is attached to the wheel hub, which is held by the upright. On the side of the upright, the caliper is attached in two points. On the inner side, the suspension elements, control arms, and steering bars are connected to the upright with ball joints. If we want to measure the angular velocity, temperature, and forces at the wheels, various sensors can be mounted on extra consoles.

The suspension elements converge at the upright, so when designing the upright, we can have an effect on how to adjust the driving dynamic properties. Changing the length of the suspension bars can affect the wheel alignment. We can make changes on the camber, caster angles and kingpin angles. There are several possible mounting points for the steering bar in order to have better steering option. [1, 2, 3]

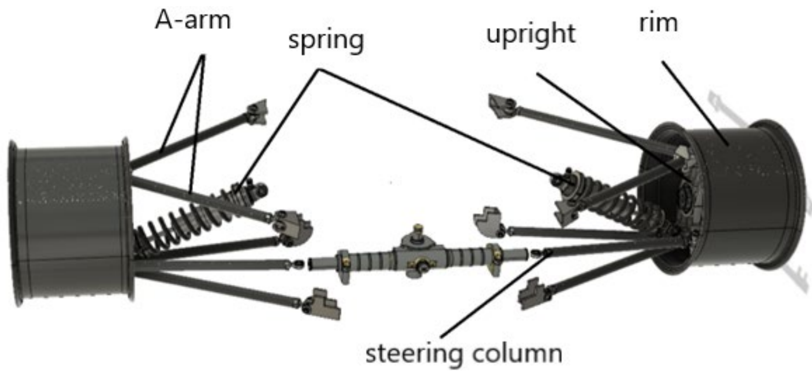


Figure 1
Geometric arrangement

The cars designed and assembled by the teams need to meet some serious requirements just like in Formula1. The uprights were designed based on the rules created by the organization Formula SAE International.

- V.3.1.1.: „The vehicle must have a fully operational suspension system with shock absorbers, front and rear, with usable minimum wheel travel of 50 mm, with a driver seated."

- V.3.1.3.: „All suspension mounting points must be visible at Technical Inspection by direct view or by removing any covers."

- V.3.1.5.: „All spherical rod ends and spherical bearings on the suspension and steering must be one of:

• Mounted in double shear

• Captured by having a screw/bolt head or washer with an outside diameter that is larger than spherical bearing housing inside diameter."

-V.3.2.4.: „The steering system must have positive steering stops that prevent the steering linkages from locking up (the inversion of a four bar linkage at one of the pivots). The stops may be placed on the uprights or on the rack and must prevent the wheels and tires from contacting suspension, bodywork, or Chassis during the track events." [4]

2 Forces Acting on the Upright

During racing, there are consecutive accelerations with full load, quick direction changes, and strong braking due to cornering. Table 1 summarizes the maximum critical forces that can affect the vehicle while cornering at high-speed in one direction. The values shown on Table 1 are based on preliminary simulations. The calculations take into account that the front-rear distribution of the mass is expected to be 40-60% influenced by the rear-mounted engine.

Table 1
Maximum forces occuring during a right-hand turn [1]

OUTER PART OF THE LEFT FRONT WHEEL						
	Static	Braking	Turning	Acceleration	Braking+Turning	Acceleration+Turning
Fx[N]	0	-2450	0	802	-3508	1859
Fy[N]	0	0	-2158	0	-2821	-1496
Fz[N]	613	1065	1167	349	1525	808
INNER PART OF THE RIGHT FRONT WHEEL						
	Static	Braking	Turning	Acceleration	Braking+Turning	Acceleration+Turning
Fx[N]	0	-2450	0	802	-1392	-256
Fy[N]	0	0	-457	0	-1120	206
Fz[N]	613	1065	247	349	605	-111
INNER PART OF THE REAR WHEEL						
	Static	Braking	Turning	Acceleration	Braking+Turning	Acceleration+Turning
Fx[N]	0	-802	0	2450	-1859	3508
Fy[N]	0	0	-2158	0	-1496	-2821
Fz[N]	613	349	1167	1065	808	1525
OUTER PART OF THE RIGHT REAR WHELL						
	Static	Braking	Turning	Acceleration	Braking+Turning	Acceleration+Turning
Fx[N]	0	-802	0	2450	256	1392
Fy[N]	0	0	-457	0	206	-1120
Fz[N]	613	349	247	1065	-111	605

The critical forces that were taken into account during the examination were defined with a 250 kg racing car in the case of a 7.625 m radius turn at a speed of 11 m/s during acceleration and braking. The maximum acceleration and deceleration for the race tires selected by the team can be 1.8 g. Exceeding this acceleration, grip (adhesion) cannot be guaranteed, and the tire may slip. During our examinations, we used the maximum forces that could occur on the wheel, so in the case of a right turn, (forces on) the outer side of the left wheel of the front axle, the inner side of the right wheel, and the outer side of the left wheel and the inner side of the right wheel of the rear axle (Figure 2).

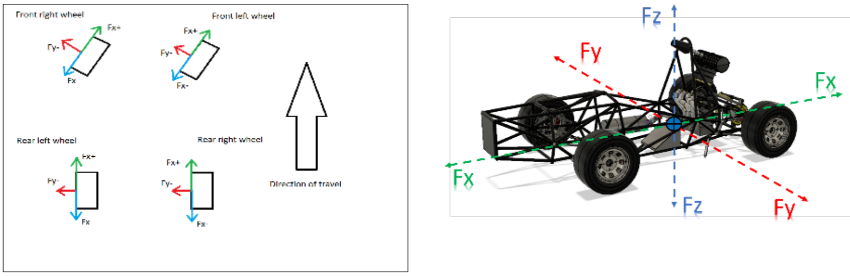


Figure 2
Presentation of the maximum forces between the wheels and the road

During braking, the brake caliper presses the brake pads against the brake disc, slowing the vehicle down. Forces and torques are generated during the friction, which must be endure by the upright. We needed the force that struck at the brake caliper attachment points. To determine that, first we had to give the necessary braking torque. The braking torque can be used to determine the force at the attachment points, if we know the force of the arm/lever.

3 Simulation of the Initial Upright

With the knowledge of the forces, we created a finite element simulation of the current geometry. The maximum forces acting differently per wheel had to be examined in separate simulations. If we had done it in the same simulation, the forces in opposite directions would not have shown realistic solutions. The upright was not designed in this program, so first we had to export the geometry from another program. The material of the upright, which was selected as AlSi7(LM25) aluminum alloy during the design, was replaced with 6061 aluminum alloy desired to be used by the team. This material is more easily available and can be found in the optimization programs used.

The preparation of an appropriate mesh grid is a basic requirement for acceptable and usable computational results. After creating the grid, we defined the forces, torques, and points of application. When specifying forces, there was an option to choose between distributed, gravitational, and point forces. [5, 6]

The forces between the tire and the road are transmitted through the bearings to the upright, but only in radial directions (on the x and y axes). In the 2022 version of the program, it was possible to separately select a bearing force effect. The program had not operated the lateral transfer of forces through the bearings yet, so the cross-directional forces had to be specified as distributed forces on the surface in contact with the bearing side wall. Afterwards, we placed an external force of 85 mm radius on the brake caliper attachment points. To define the steering force, we exerted force on the steering link attachment point as shown in Figure 3.

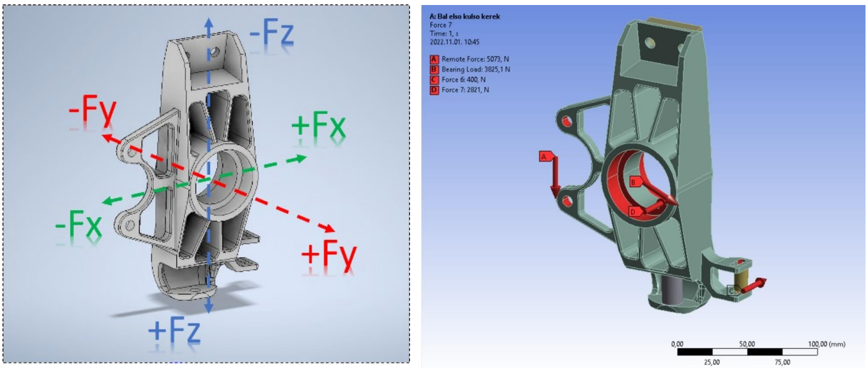
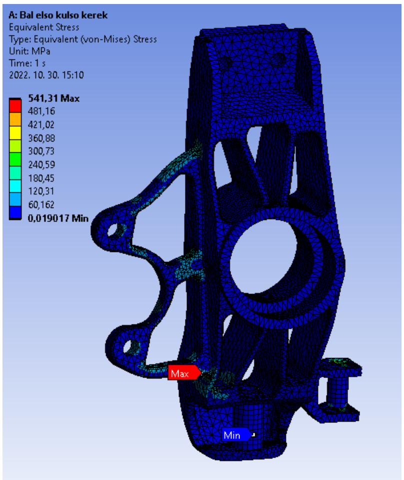


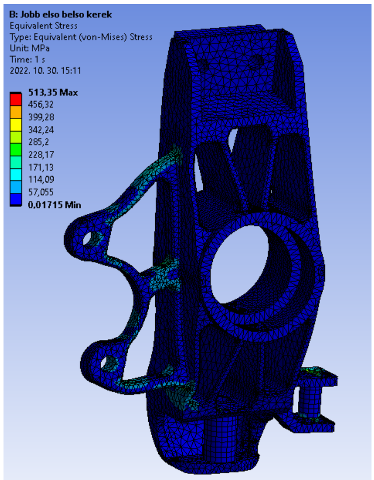
Figure 3
Defining the force effects in ANSYS

During the meshing procedure of the uprights, we used tetrahedral elements. The maximum of 128,000 nodes provided by the Ansys Mechanical Student version proved to be sufficient for the detailed meshing of the upright's structure. To ensure accurate representation of the results, local mesh refinement was applied at necessary locations. Quadratic element order was used in the mesh construction.

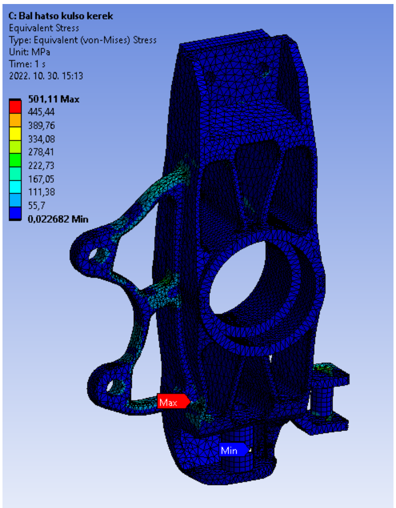
The suspension arms were connected with the help of shafts, which were attached to the pre-shaped parts of the upright with a screw-nut combination. With this type of fastening, we applied pre-tension, which the structure also had to withstand. The magnitude of the pre-tensioning force was approximately 4000 N based on the experience of other teams. The maximum geometric deformation (Total Deformation) and the stresses acting on the body (Equivalent Stress) were examined as a result of the specified forces and constraints. As can be seen from Figure 3 and Table 2, the starting upright and the selected material do not meet our expectations. Although our deformation values are in the appropriate range, the stress values and the safety factors derived from them are not. The desired strength properties can be achieved in two ways: by using a stronger material selection, which generally leads to an increase in mass, or by creating a more favorable structural design.



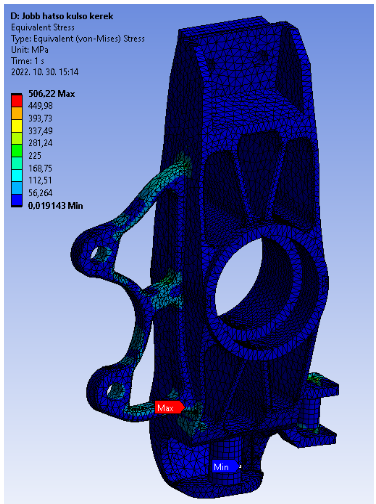
Upright for the left front wheel



Upright for the right front wheel



Upright for the left rear wheel



Upright for the right rear wheel

Figure 3
The Von Mises stress distribution of an initial upright designed ANSYS

Table 2
Simulation results of starting upright in ANSYS

ANSYS	**Category**	**Mass [g]**	**Material**	**Max. stress [Mpa]**	**Min. safty factor**	**Deformation [mm]**
Initial upright	Left front wheel outer	530	6061 Alumínium	541	0,51	0,22
Initial upright	Right front wheel inner	530	6061 Alumínium	513	0,54	0,22
Initial upright	Left rear wheel outer	530	6061 Alumínium	501	0,55	0,24
Initial upright	Right rear wheel inner	530	6061 Alumínium	506	0,54	0,22

3.1 Mass and Structural Optimization

During the optimization, we strive to achieve the best possible state or result based on a pre-determined criterion. In technical life, we know several types of optimizations. While the optimization of a production process may be more common, the optimization of a component's mass, structure and resistance to external effects is the most well-known during the development of a component. Mass reduction can be achieved by reducing volume or using a more favorable density material. We performed several studies although I will not go into in detail now. [7]

One of the optimizations we carried out was executed with generative design. Firstly, we ranked the obtained bodies by mass. This was important because our goal was to reduce mass and optimize the structure. In addition to the mass, we also had to take into account the production method and safety factors. The choice was made with 5-axis machining, made of titanium 6Al-4V material, with a safety factor of 2 and a total weight of 327g.

This type of alloy is a much denser material than aluminum, yet less quantity was used so that it can be considered successful in terms of weight reduction. This is partly due to the mechanical strength of the material. The resistance of the external effects on the body and the structural strength of the upright can be evaluated with the help of simulation programs.

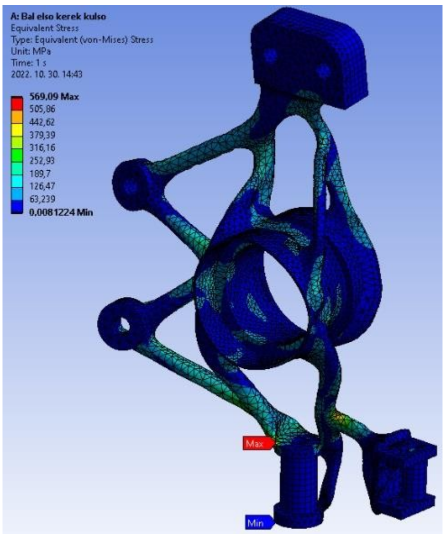
During the second optimization method, the shape optimization, we wanted to lay emphasis on the presentation of the differences between the construction of the old and the new bodies, so we chose aluminium 6061 as the examination material. Compared the initial upright, we managed to achieve here nearly 20% (19,2%)mass reduction.

With design methods supported by AI, a lot of time can be saved, and such results can be achieved, which would be impossible with traditional design methods. Not surprisingly, it is used more frequently when the aim is to reduce mass. In Hungary, more racing teams have used it for working processes. AI helped design a suspension part by the BME Formula Racing Team, an upright and a rim by the Arrabona Racing Team. We can find more examples of the achievements of AI internationally.

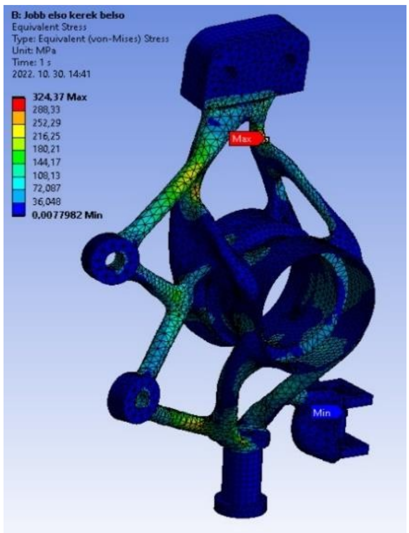
Besides the public sector, artificial intelligence-design is on the rise in the industry. One notable example is the Czinger 21C hypercar, which was created with generative design and additive manufacturing methods in 2020. The production of the vehicle started in 2021 and the first cars will be ready by 2023. [8, 9, 10,11]

3.2 Static Finite Element Simulation Results of the Designed Uprights

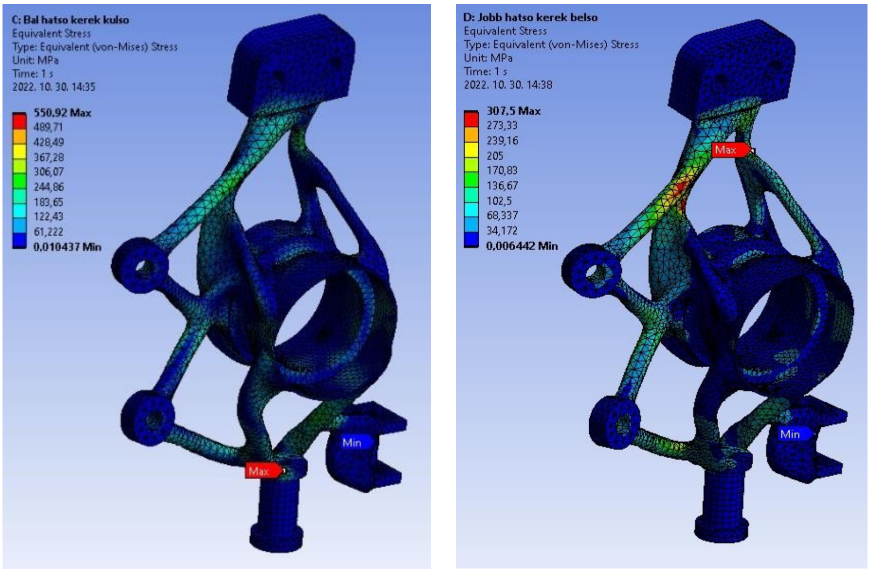
The optimized bodies were examined from a strength point of view, with constant/static and transient simulations. Dynamic effects were ignored because the regulations for the race track are strict. These various unevenness and dynamic loads are not allowed. During the examinations, we took into account that the initial geometries had to be in the same plane in order to be comparable. The simulation runs were checked and compared to the results of the initial body. Specifically, we made sure that the connecting parts of the initial geometry that needed to be left free for simulation purposes were in contact with prohibited zones. This way, the vehicle's internal coordinate points of the connection points did not change, so the same forced and constraints were placed on the new body like on the initial body. After the simulations had been run, we examined and compared the results with results of the initial body.



Upright for the left front wheel



Upright for the right front wheel

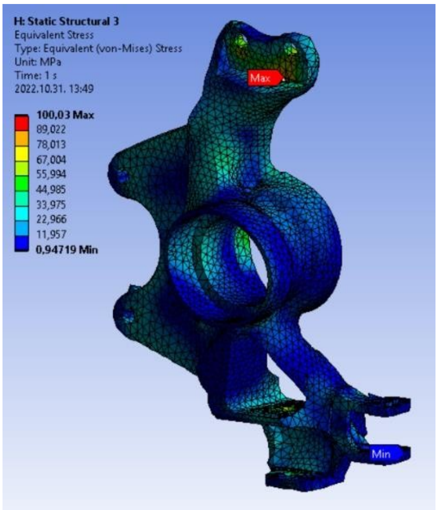


Upright for the left rear wheel Upright for the right rear wheel

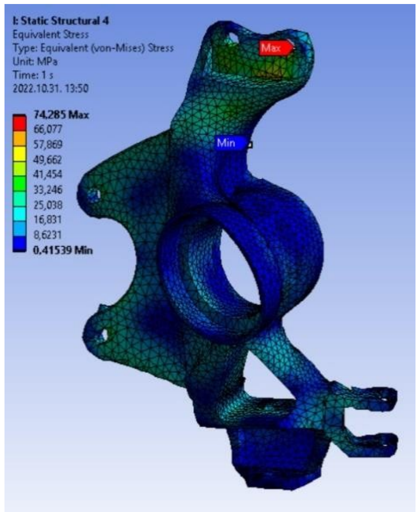
Figure 4
The Von Mises stress distribution of an upright designed with shape optimization while presenting deformation

Table 3
The results of the simulations of the initial upright in the ANSYS program

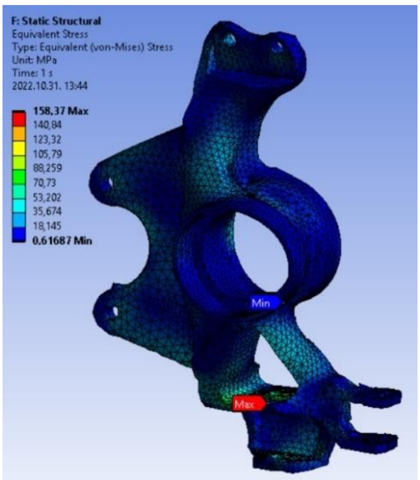
ANSYS	**Catergory**	**Mass [g]**	**Material**	**Max. stress [Mpa]**	**Min. safety factor**	**Deformation [mm]**
Generative design	Left front wheel outer part	327	Titan Al6-V4	569	1,55	1,1
Generative design	Right front wheel inner part	327	Titan Al6-V4	324	2,7	0,78
Generative design	Left rear wheel outer part	327	Titan Al6-V4	551	1,6	1,31
Generative design	Right rear wheel outer part	327	Titan Al6-V4	308	2,87	0,73



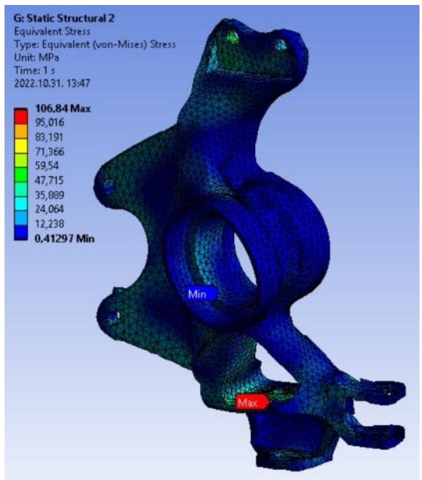
Upright for the left rear wheel



Upright for the right rear wheel



Upright for the left front wheel



Upright for the right front wheel

Figure 5

The Von Mises stress distribution of an upright designed with shape optimization while presenting deformation

In order to get more information about the construction of the upright, we did transient simulations too. During the transient simulation, we examined the acceleration process followed by braking in a curve, with the highest possible acceleration due to tire adhesion. We examined during transient finite element simulation. The boundary conditions of forces can be seen in Table 1.

Table 4
The results of the simulations of the initial upright in the ANSYS program

ANSYS	**Category**	**Mass [g]**	**Material**	**Max. stress [Mpa]**	**Min. safety factor**	**Defromation [mm]**
Shape optimization	Left front wheel outerpart	428	6061 Aluminium	158	1,74	0,21
Shape optimization	Right front wheel innerpart	428	6061 Aluminium	107	2,57	0,11
Shape optimization	Left rear wheel outer part	428	6061 Aluminium	100	2,75	0,19
Shape optimization	Right rear wheel innerpart	428	6061 Aluminium	74	3,71	0,11

4 Results

Overall, we can say that there was an improvement in terms of the mass of the bodies in the case of both redesigned uprights. With generative design, the value was reduced to 327 grams, and with the help of topological optimization, it was possibleto reduce it to 428 grams. If we managed to achieve nearly 20% or more mass reduction in all parts of the vehicles, we could see improvement in fuel consumption and in the characteristics of driving dynamics as well.

During the optimization, we were also able to achieve the goal of maintaining or even increasing the structural strength of the construction of the upright, despite the mass reduction, thus preserving or even increasing the safety of use.

According to Fusion 360, a part can be made with five-axis machining, but the result from generative design would be 3D printed due to the thin geometries.

Conclusions

The best choice of the upright optimization is the one with topological optimization. The generative design is not perfected although it can draw the attention to ours. One benefit of the topological optimization is that the geometry created with this method has better deformation values than the geometry made by the generative design. We managed to keep the deformation value at nearly 0.2 mm. In the case of the generative design controlled by AI, this value exceeded 1 mm. We can say that we did not succeed in making such as breakthrough in the field of mass reduction with the topological design as with the generative design. However, as we need a reliable construction for the first racing car of the team, overall, the shape optimization method is the ideal choice.

The research can be continued with other parts of vehicles as well. This technology can be used in a number of other industries where the efficiency of processes can be increased by mass reduction. Despite the results in the private sector, the parts manufactured in piece production in a similar way do not usually end up in mass production. If there was a technology enabling the fast and precise production of these bodies/shapes, the design methods that I showed would have more importance.

In the future, we aim to conduct more thermodynamics and fluid dynamics simulations in order to get more important information about parts.

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