University of Twente
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Design for additive manufacturing

Optimization of an aircraft part for additive manufacturing

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1 Introduction

Additive manufacturing has seen an uprise in the last few years. It can offer advantages over traditional manufacturing technologies, for example, weight reduction, increased efficiency by reducing waste, freedom of design, and part consolidation. By building the part layer by layer, some geometries can be produced that were not possible before. These new possibilities ask for a new way of designing. Complex optimized geometries are more norm than exception.

An unnamed aircraft manufacturer intends to replace an assembly that consists of 3 separate parts (see figure 1). The manufacturer wants to know its options for additive manufacturing. The key features of the part including their position, being the 3 mounting holes for attaching the component to the aircraft, the force input shaft, and the sensor, must remain unchanged, but the connections between the three are free to redesign.

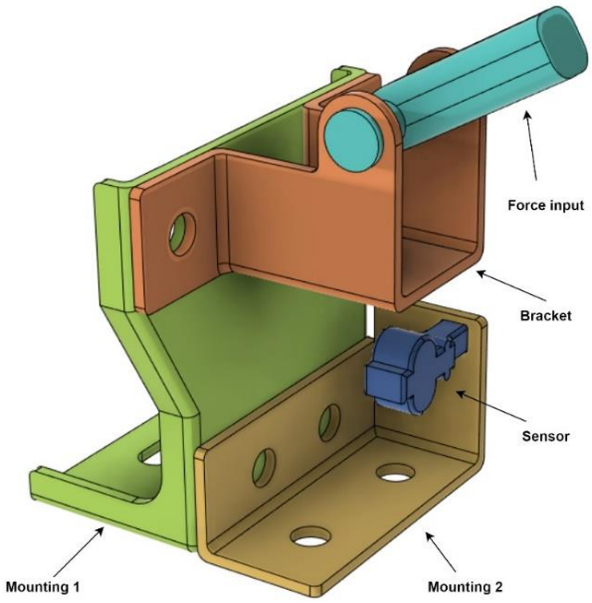


Figure 1: Aircraft assembly components

2 Assignment

The goal is to incorporate additive manufacturing into the manufacturing process in order to reduce lead times while offering opportunities for design optimization, including improvements in weight, performance, manufacturability, maintainability, and costs.

3 Topology Optimisation

The Topology optimization process is an iterative process that is also linked to additive manufacturing. The process starts with a strategy.

3.1 Strategy and iterations

Safety is the single most important factor to consider in aviation. The risks and collateral damage (loss of lives, injuries, negative public perception, and negative financial consequences) are simply too high to allow for compromises in terms of component performance. Therefore the new component must at least meet the performance of the current assembly. The second most important factor is weight reduction in aviation to allow for more payload or better fuel economy. Under the assumption that margins in the aircraft industry are very tight, cost reduction is the third most dominant factor to consider. Next, manufacturability and maintainability will be considered. Because it is unknown whether this part is visible, appearance is considered as well. Ordering these assumptions is important since there will be tradeoffs to be made when redesigning the assembly. This is more deeply discussed in section 4.

In order to have a benchmark, the current design was analyzed with regard to its performance. The results of this analysis will be compared with the new design in section 6.

The following four main iterations led to the final design. Each iteration will be explained in more detail in the following subsections.

1. Initially the current assembly was used as a starting point for topology optimization. For this, the three parts were consolidated into a single part. In different iterations, the material was added and removed utilizing shape optimization studies within Fusion 360. This however did not lead to satisfying results and therefore this strategy was quickly abandoned.

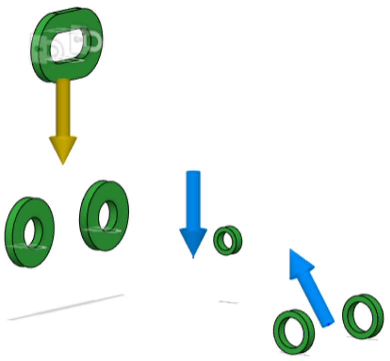
2. Generative design allows for great weight reduction whilst improving performance, utilizing the freedom of design and therefore organic structures. A generative design study was done to act as inspiration for what optimal designs could look like. One of the designs was aesthetically pleasing and therefore chosen. A redesign from scratch was then performed in different iterations that led to a bracket that outperformed the original assembly, however upon the simulation for manufacturing the design showed the need for supports that upon removal would increase the cost. Therefore a new goal was set, namely to start over and come up with a design that would not need additional supports.

3. The second redesign was again performed in multiple iterations (static study $\rightarrow$ shape optimization $\rightarrow$ positioning and support analysis $\rightarrow$ distortion compensation analysis $\rightarrow$ heat treatment analysis) and led to a bracket that only needed 3 supports at the mounting locations and 3 supports within the holes for the sensor and force input shaft.

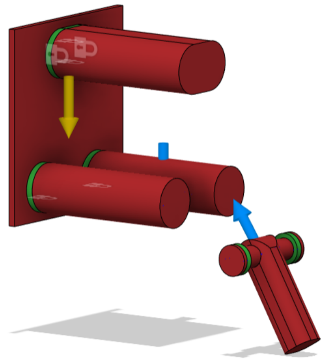
4. The fourth and fifth iterations were to create designs that were aesthetically more pleasing. This way, the aircraft manufacturer has a choice between multiple brackets. As it turned out, the fourth iteration did not outperform iteration 3 in all areas, however, it was still outperforming the original design in all aspects. The fifth and final iteration provided a design that outperformed all previous iterations in every way except for weight. Although it is heavier, it will be explained why this design is favorable above all others.

3.2 Simulation setup

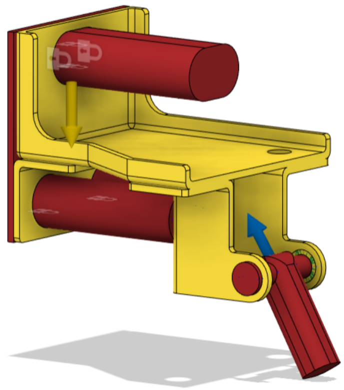
The simulation setup is similar for the topology, generative design, and static load. In all simulations, the load information as specified by the manufacturer is applied on their respective surfaces. The 2 empty holes and the slot for attachment to the airplane are constrained in the x,y, and z directions. For the topology optimization and the generative design a preserved area was set for the flange of the boltheads, sensor mounting, and force input shaft. Since the holes for mounting are 10 mm in diameter, a DIN6921 M10 bolt was assumed as a fastener. This bolt has a flange diameter of 22.3 mm. The flange of the force input shaft has a diameter of 14 mm. The minimum amount of material around the sensor mounting hole in the original design is 3 mm, so in the new design, this was also set as a minimum preserved area as can be seen in Figure 2a. In addition, a mounting area as large as the original contact surface, the sensor, the force input shaft as well as three volumes to allow the bolts to slide into their holes were defined as obstacle geometry as depicted in Figure 2b. Finally, the original assembly was selected as the starting shape (Figure 2c).



(a) Loads, constraints and preserved areas



(b) Loads, constraints, preserved areas, and obstacle geometry

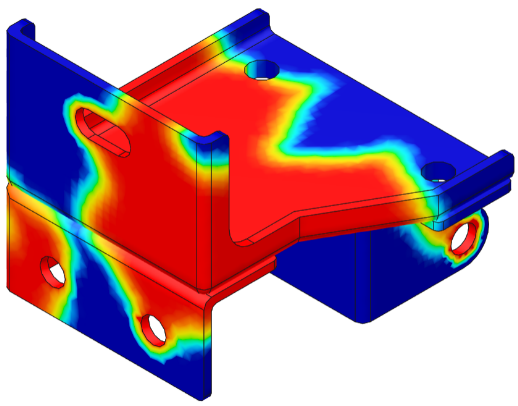


(c) Loads, constraints, preserved areas, obstacle geometry and starting shape

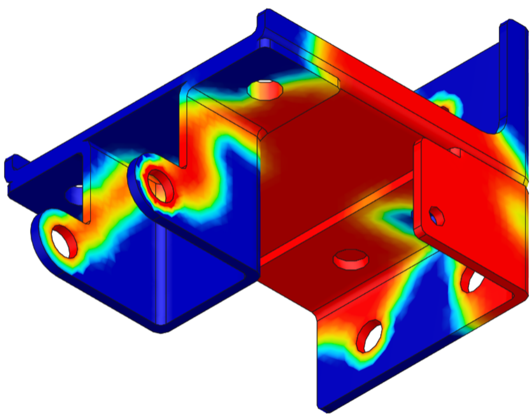
Figure 2: Simulation setup

3.3 Iteration 1

The original part is optimized for plate material and does not use any of the benefits of additive manufacturing. A first topology study on the original design shows that many parts can be removed. Figure 3 shows this simulation.



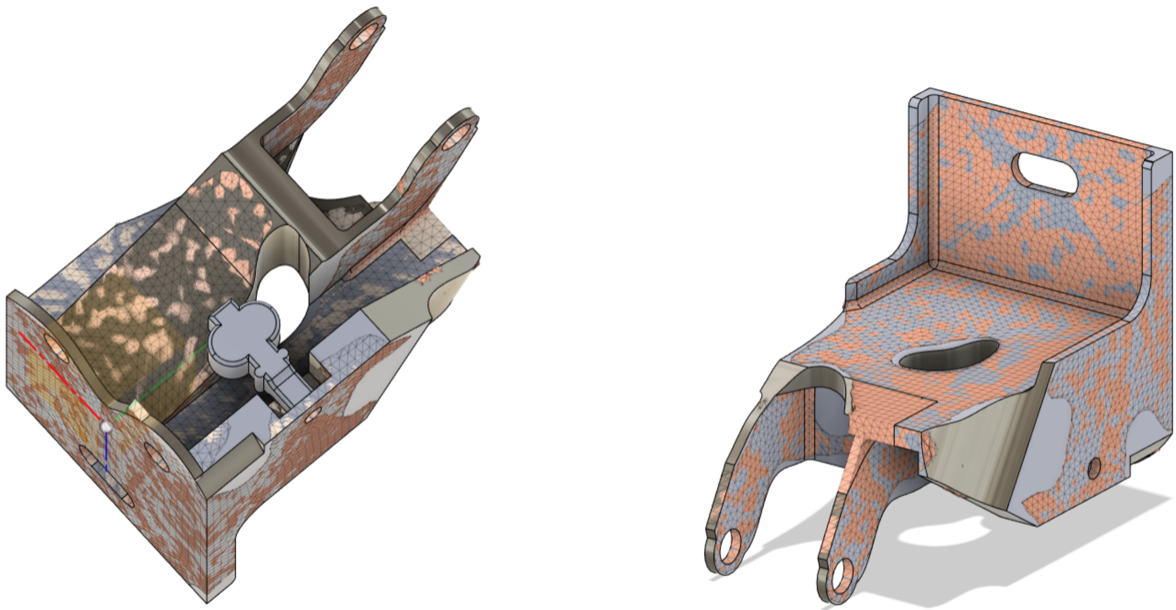
(a)



(b)

Figure 3: Topology study on the original part as provided by the manufacturer

Material was added and removed in different locations from the original part. This did however not result in an appealing design. This route was therefore discontinued halfway through (Figure 4) and a new design was made. To come up with ideas for a new and better design, a generative design study was done for inspirational purposes.



(a) (b)

Figure 4: Topology iteration 1 by adding and removing material from the original bracket

3.4 Iteration 2

The result from the generative design study can be seen in figure 5. A model was started by beginning with the preserved areas as previously defined. The new design is made with organic shapes that remove sharp corners and make the design lighter with a higher stiffness.

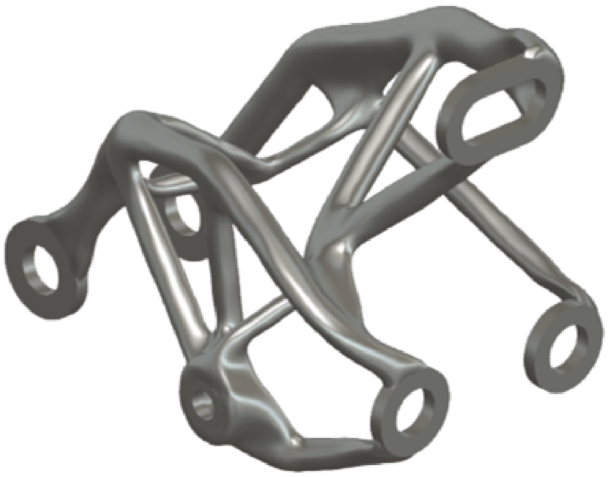


Figure 5: Result from the generative design study

As discussed in section 3.1, also in this iteration, the material is removed and added based on the results from the various simulations. The final design from this phase can be seen in figure 6. The problem with this iteration, however, showed during the simufact simulations, where it became clear that an excessive amount of support structures would be needed. Since this will add costs (material and support removal costs) and it seemed feasible to create a design that would allow for less supports, another design was created (iteration 3). Because it was unclear whether iteration 3 would lead to a successful design, iteration 3 was fully completed including all simufact simulations such as distortion compensation.

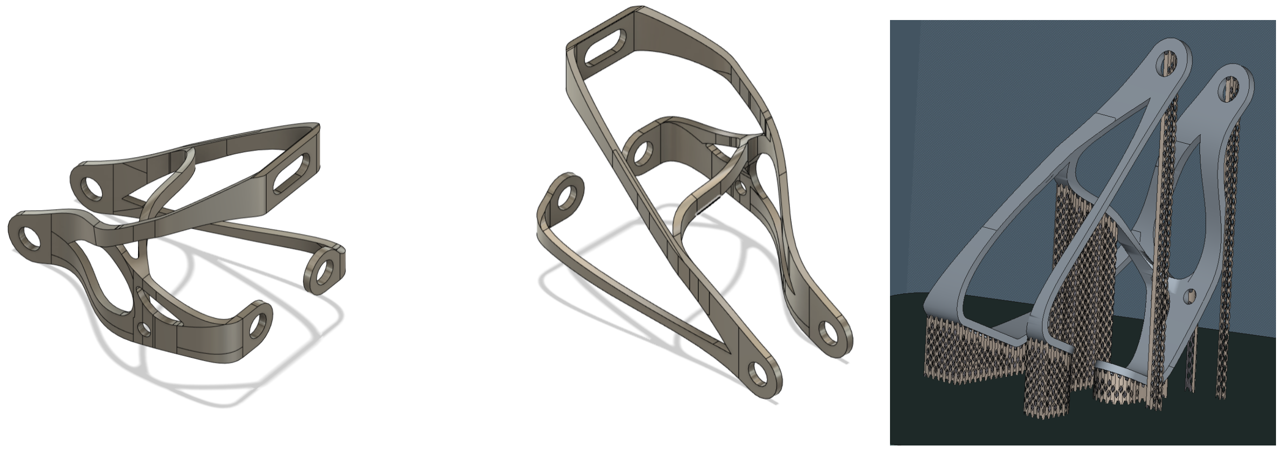


Figure 6: Design optimized for performance, but not for additive manufacturing

3.5 Iteration 3

For this iteration, the goal was to design a bracket that would not need any unnecessary support structures. Figure 7 shows the result after many iterations and simulations of a design that does not need additional support structures. The numerical performance is shown in table 2. Because people like to have a choice, it was decided to come up with alternatives for iteration 3 that would provide different aesthetics.

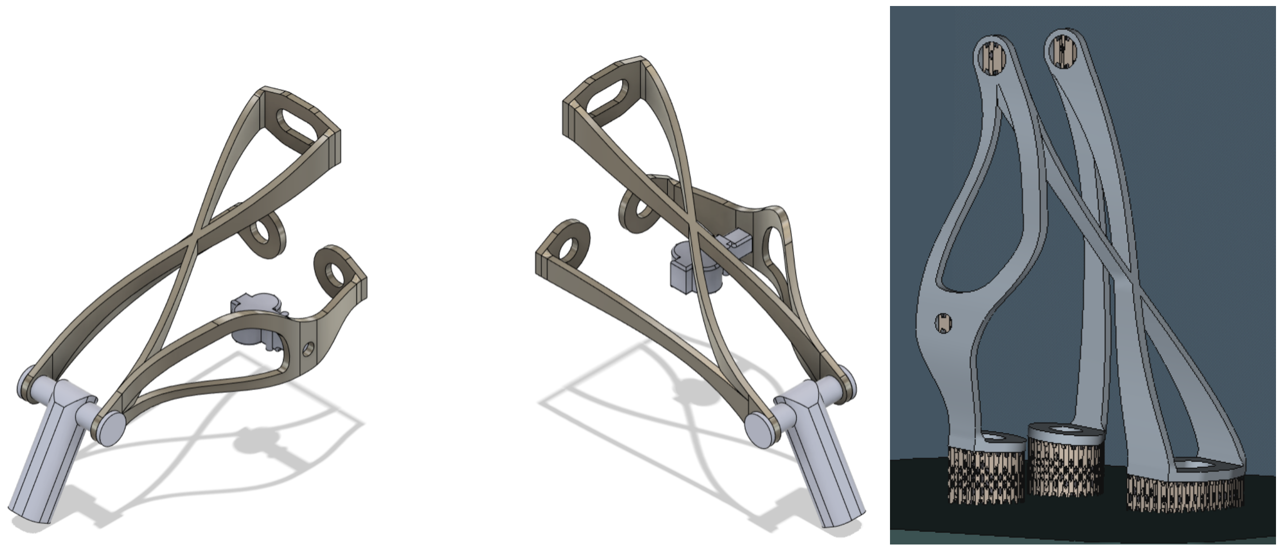


Figure 7: Design optimized both for performance and additive manufacturing - iteration 3

3.6 Iteration 4 & 5

Iteration 4 has been created to improve the aesthetics and handling of the design from iteration 3 by smoothing edges and corners. This resulted in the design seen in Figure 8. With this iteration, the numerical performance has partially improved further, with a drawback of a small mass increase, as seen in table 2.

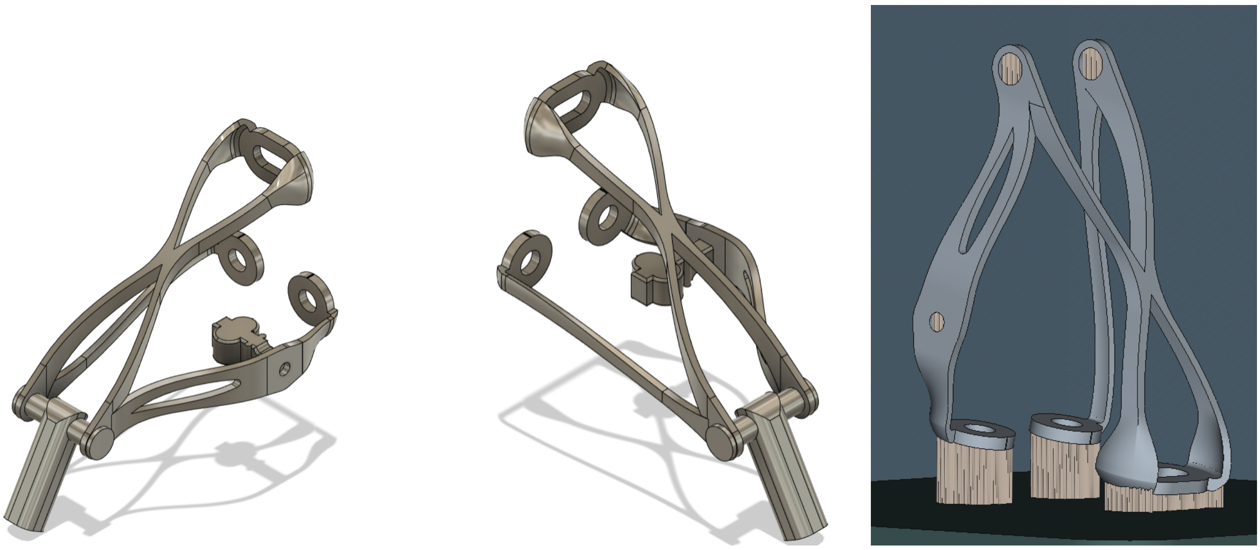


Figure 8: Design optimized both for performance and additive manufacturing - iteration 4

While making the design for iteration 4, it became clear that the part could be further improved, both performance-wise and aesthetically. This resulted in the next and final iteration 5, which can be seen in the figure 9. This iteration has improved performance when compared to iteration 4 while remaining the same weight and it also allows for more tool clearance in the upper mounting slot.
It is the smoothest and the best performing out of all the iterations except for weight. It is 2 grams heavier than iteration 3, however, it outperforms iterations 3 and 4 significantly, as table 2 shows.

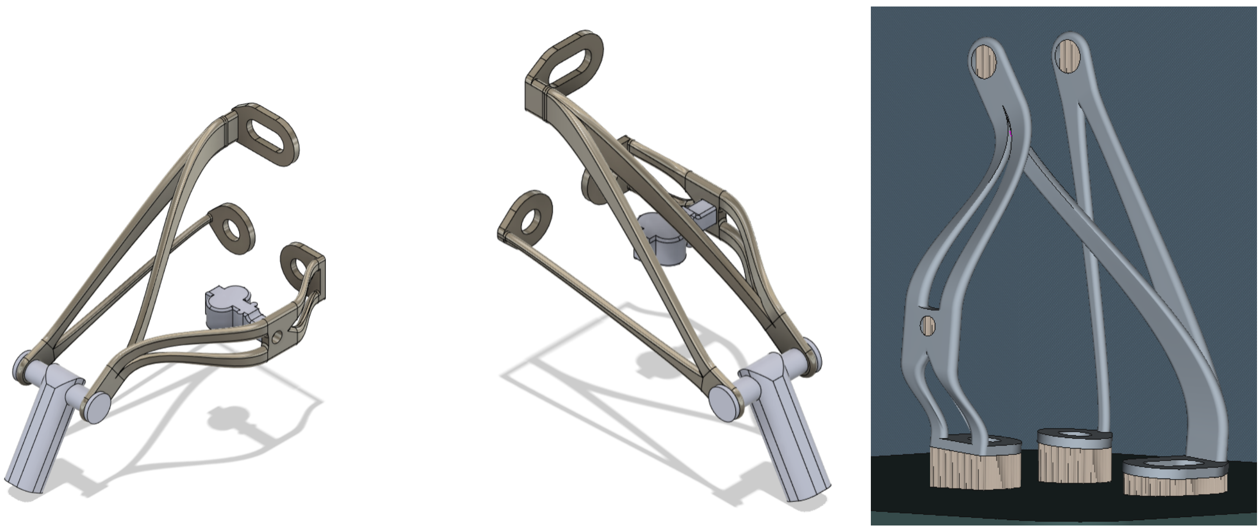


Figure 9: Design optimized both for performance and additive manufacturing - iteration 5

4 Additive manufacturing

4.1 Strategy

For additive manufacturing, the focus was on decreasing the costs whilst outperforming the original bracket. This was accomplished by designing out all supports except those that are strictly necessary. These necessary supports are the holes for the sensor and force input shaft and the bottom where the bracket connects to the build plate. This surface is also the interface between the aircraft structure and the bracket. Having a clean and smooth surface is necessary to avoid any interface issues when fastening the bracket and using the bracket to transport the forces from the shafts to the structure of the airplane.

4.2 Design guidelines

To remove all the supports, the design has no angles that have an overhang of more than 45 degrees. This results in smooth curves to accomplish this. The warp compensation changes the original design. This change must also not go over the 45-degree limit. This was tested, and compensation did not cause any problems with supports as can be seen in Figure 10.

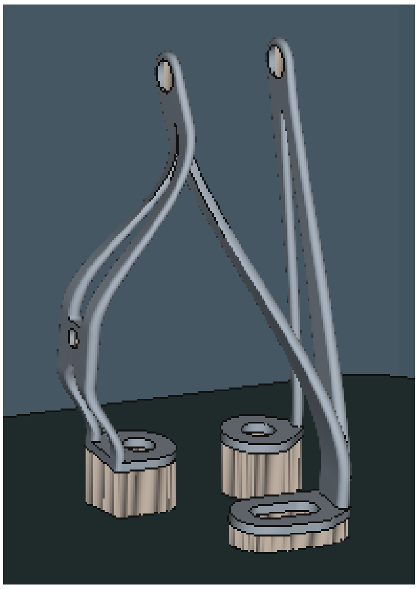


Figure 10: Compensated model with supports

4.3 Orientation

The orientation assistant positioned the bracket in such a way, that the support volume and support area was minimized. This however resulted in multiple surfaces needing support, which in turn would increase the costs of the product due to extra removal costs for non-critical surfaces, which were not specified in the simulation. By positioning the bracket with the mounting surfaces down, a minimum of surfaces needed supports. Choosing the critical surfaces as supported surfaces is wise since those surfaces need post-processing anyway (see Figure 11), at the trade-off of adding material cost. The manual positioning requires additional support material, however, it takes less time to print as table 1 shows. A comparison is shown in Figure 12. Therefore manual positioning was chosen.

	material costs	extra support removal costs	total cost	extra build time
manual positioning	€ 135.64	-	€ 135.64	-
positioning assistance	€ 114.80	€ 120	€ 234.80	1h20m

Table 1: comparison of positioning assistance and manual positioning

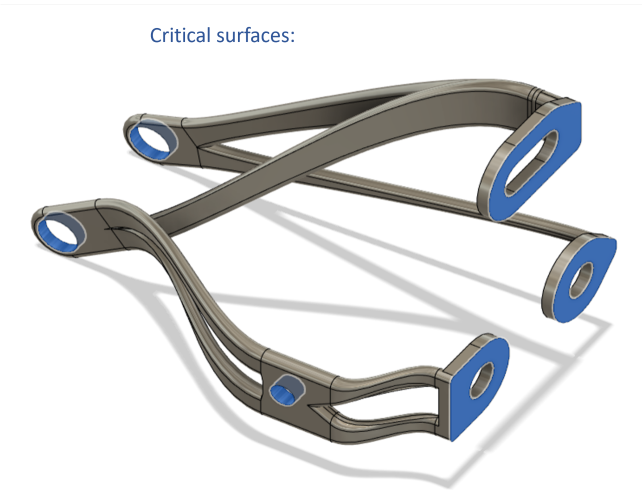
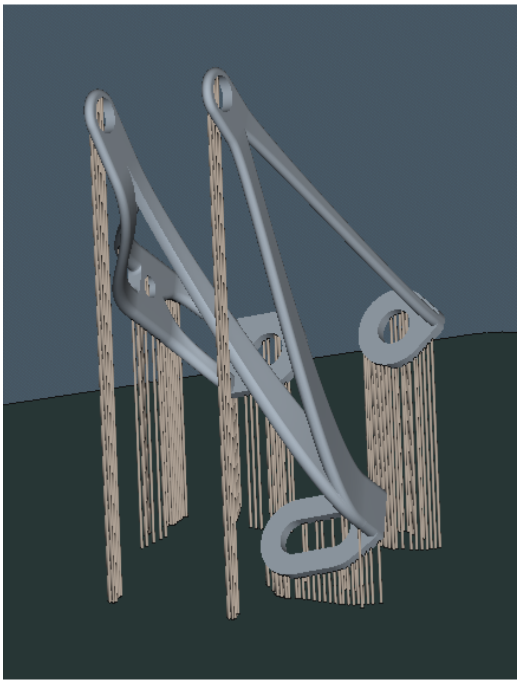
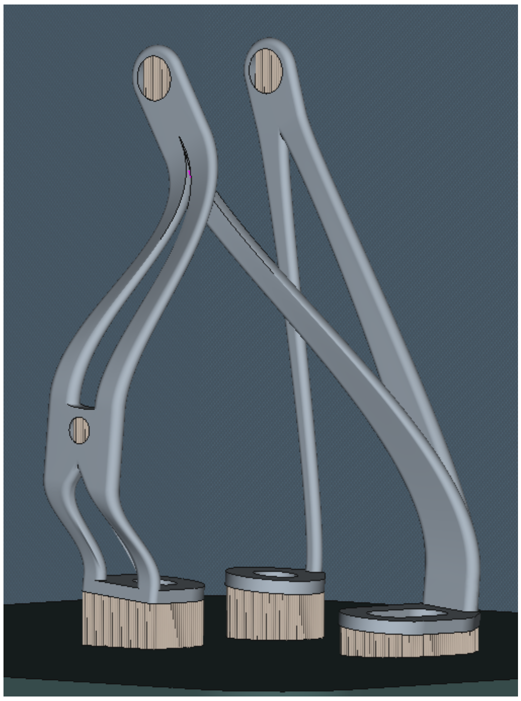


Figure 11: Critical surfaces marked in blue



(a) positioning assistant



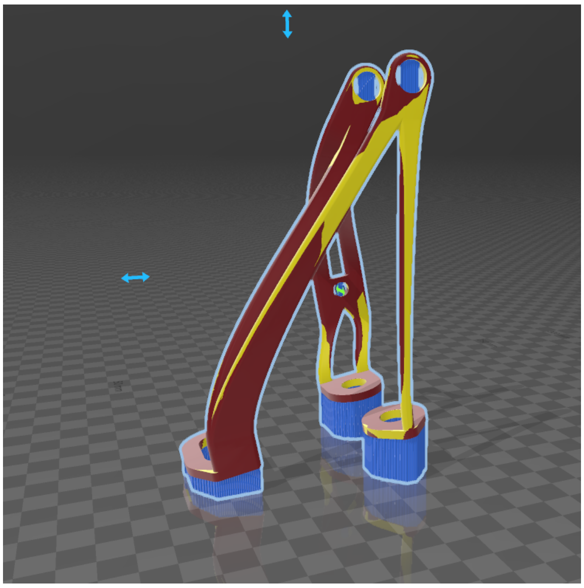
(b) manual positioning

Figure 12: Orientation optimized for costs

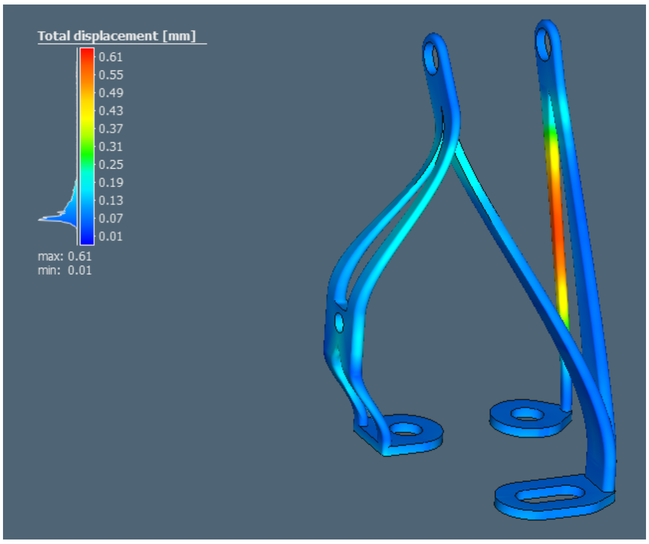
4.4 Simufact simulation parameters

For the simulation, the following steps are set: Build, heat treatment, cutting, and support removal. The part is positioned 5 mm above the base plate. The material is set at the ti6al4v alloy. After this, the supports are generated with the simufact method. To compensate for the warping of the part after the process, distortion compensation is set to a maximum of 10 iterations with a goal of acceptable distortion of 0.1 mm, with all variants saved. The process parameter for the heat treatment length is set to 1800 seconds. The cutting height is set at 1 mm. All supports must be removed. The voxel mesh is set to a size 1.5 mm (uniform).

The simulation showed almost no distortion on most of the parts, except for one of the linkages, which had a displacement of 0.61 mm (Figure 13b). This part of the linkage is not a dimension-critical surface, but the distortion is still out of the given allowance of 0.1 mm, so distortion compensation had to be calculated. After calculating the compensation, the distortion went from 0.61 mm to 0.08 mm in one iteration(Figure14a). The print risk was also evaluated, at a slice height of 1 mm, and no risks were found (Figure14b). Results of the compensation can be seen on the mesh-overlapped view in Figure 13a.

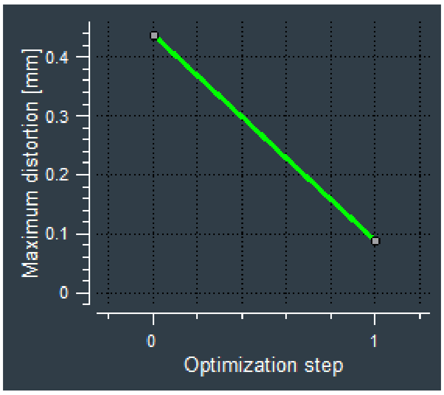


(a) Comparison of the compensated model (Yellow) with the original geometry (red)

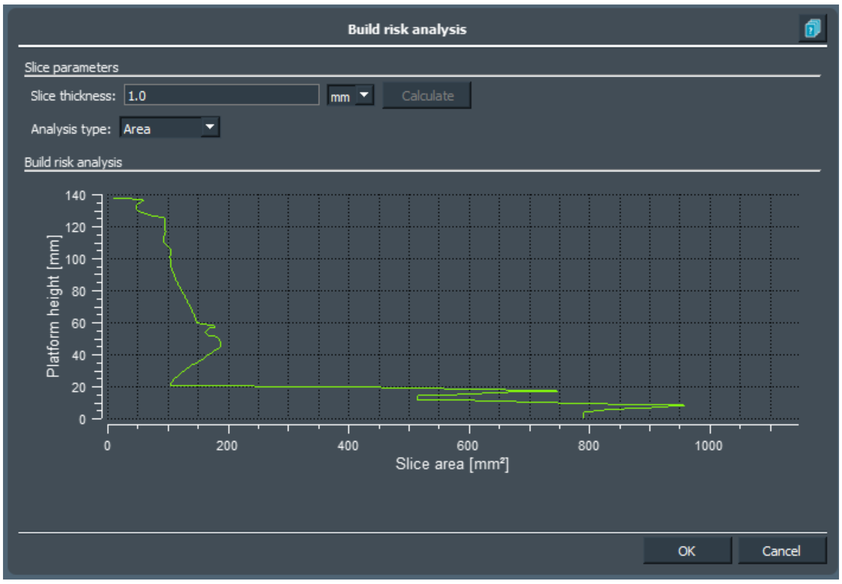


(b) Pre-compensation manufacturing process results

Figure 13: Simulation results - models



(a) Graph of the compensation process parameters



(b) Risk analysis of the compensated model

Figure 14: Simulation results - graphs

4.5 Results

Iteration	Safety factor	Stress $[MPa]$	Displacement $[mm]$	Mass $[g]$	δ safety factor		δ stress $[MPa]$		δ displacement$[mm]$		δ mass$[g]$	
original	1.208	730	4.101	363								
3	1.375	642	1.551	77	0.16	+13.8%	-88	-12.1%	-2.55	-62.2%	-286	-78.8%
4	1.421	621	1.979	79	0.213	+17.6%	-109	-14.9%	-2.122	-51.7%	-284	-78.2%
5	1.448	609	0.897	79	0.240	+19.9%	-121	-16.6%	-3.20	-78.1%	-284	-78.2%

Table 2: Comparison of different engineering parameters between different iterations and the original part

5 Cost calculation

The costs of producing the part can be split into 2 categories, the printing costs and the post-processing costs. The printing costs consist only of the material costs. The costs for personnel, machine depreciation, and electricity are not taken into account. Although, it is worth noting that the printing time has been simulated to be 16.5 hours. During the printing, a total of 116.11 grams of titanium is used. This includes both the part and the added supports. According to (Vaneker et al)[1] Titanium powder for laser powder bed fusion costs €5,68 per cm^3. 10% was added for post-processing which must be added to this price. With the density for ti6al4v of 4420 kg/m^3[2] this results in a material cost of €135,64.

The costs for post-processing can be split into heat treatment, the removal of the part from the build plate, removing the supports from the part and finally reworking the critical surfaces. The heat treatment costs around $500-$2000 according to Vaneker et al.[1] Due to the small size of the parts, the lower end of this range is chosen. For the part removal with a bandsaw, no price indication is given as the costs are neglectable.

In total six supports are added during the printing process. Support removal of critical surfaces costs €60 per surface. There are three holes in which supports are added. The other three supports are on the bottom side of the part where it connects to the printing bed. Since the three mounting surfaces all lie in the same plane, it is assumed that it counts as one surface for this cost calculation. In total this comes to 4 critical surfaces where support has to be removed resulting in a cost of €240,-.
Due to the use of the distortion compensation the design stays within the required 0.1 mm of tolerance. This removes the need to rework the critical surfaces that are out of specification. Also, there is no need for machining of critical surfaces, since it is assumed that this is already done as part of support removal.

Printing	
Powder	€ 135,64
Post Processing	
Part Removal (Bandsaw)	€ 0
Heat treatment	€ 500
Machining	€ 0
Support removal normal	€ 0
Support removal critical	€ 240
Rework critical surfaces	€ 0
Total	€ 875,64

Table 3: Overview of the costs for producing the part

6 Conclusion

The original aircraft part was sufficient for its purpose, but many improvements have been made with additive manufacturing. The original design is completely abandoned in favor of a more appealing and performing design. The results (section 4.5) from the design phase show great improvements in weight, safety, and displacement. To reach the final design, it took roughly 30 simulations per interaction in Fusion360 and about 10 in Simufact to get the model optimized in the manufacturing process. The final design has increased the safety factor by 19.9% while decreasing the weight by 78.2% and the deflection under load by 78.1%. With simufact an orientation is found where no additional supports are needed, this results in the least amount of costs. The distortion compensation allowed the design after printing to be within the specification. This removed the need to rework the critical surfaces. In total the costs are calculated to be €875,64. Unfortunately, we cannot compare this to the price of the original assembly, since its price is not mentioned and not all of the costs had been included in the cost calculation.

This assignment has also provided a steep learning curve in terms of software usage and designing for additive manufacturing with its specific constraints.

In addition to the computer design, a physical representation has been created (Figure 15) to aid the thinking process and advocate for the design. This model will be handed in together with this report.

Figure 15: Physical model

7 Recomendation

The newly created part has several improvements and achieves all requirements but some things could be looked at in further detail. First up, the residual stresses that are in the part after the printing could be beneficial. If the residual stress proves to be beneficial, one could leave out the heat treatment, which would reduce the cost significantly (€875.64 to €375.64). A lot of weight has been removed from the original part but even slightly more could be removed at the cost of intense labor. There are a few spots where the topology optimization suggests removing material. Removing material in those locations, however, resulted in more support needed. Additional analysis could be done on how to remove material without adding supports. This however would require a lot of additional labor, which costs would exceed the decrease in material costs. Lastly, repositioning of the sensor would lead to an even more optimized design. For now, this was not allowed, but the analysis could reveal the financial and performance benefits to the manufacturer.

References

[1] Tom Vaneker et al. "Design for additive manufacturing: Framework and methodology". In: *CIRP Annals* 69.2 (2020), pp. 578–599. DOI: `https://doi.org/10.1016/j.cirp.2020.05.006`. URL: `https://www.sciencedirect.com/science/article/pii/S0007850620301396`.

[2] *Grade 5 (Ti-6Al-4V, 3.7165, R56400) Titanium :: MakeItFrom.com — makeitfrom.com.* `https://www.makeitfrom.com/material-properties/Grade-5-Ti-6Al-4V-3.7165-R56400-Titanium/`. [Accessed 23-04-2024].