Design for Additive Manufacturing

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Contents

1 Introduction

Additive Manufacturing (AM) transforms the aircraft industry by enabling innovative designs, reducing material waste, and improving manufacturing efficiency. An aircraft manufacturer is looking to optimize the assembly shown in Figure 1. In this project, we will look at how this can be done by replacing the three existing components (mounting 1, mounting 2 and the bracket) which are currently fabricated from titanium alloy using a hot forming process. By optimizing these parts for AM using Laser Powder Bed Fusion (LPBF) and topology optimization, the manufacturer seeks to reduce lead times, weight, costs, and improve performance and manufacturability. The sensor and force input must remain unchanged, as well as the bolts.

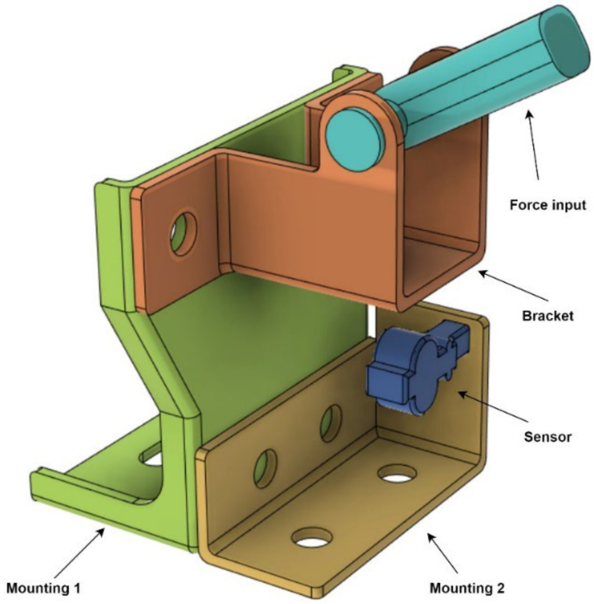


Figure 1: Components of the aircraft assembly

In this report, we will outline our strategy for optimizing the parts and present several simulation results. Topology optimization will be performed using Fusion 360, while SimuFact will be used to simulate the AM process. Additionally, all design guidelines for LPBF will be applied, and a detailed cost analysis will be conducted.

2 Problem specification

The main goal of this project is to design the parts in a way that will keep costs low, while the part should be lightweight as well. To accomplish this, the functional and technical requirements were established as shown in Table 1.

Table 1: Technical requirements

No.	Description
TR1	The total weight of the assembly should be reduced by 70%
TR2	For the interfaces (bolts/sensor) a tolerance of 0.5 mm should be maintained
TR3	The part should be able to withstand the load as given in Table 3
TR4	The three bolted holes should be fully constrained in all directions (X, Y, Z)

In addition to the technical requirements, there were also functional requirements for the parts as shown in Table 2.

Table 2: Functional requirements

No.	Description
FR1	The parts geometry should be optimized for LPBF
FR2	The manufacturing costs should be minimized
FR3	The number of supports required during printing should be minimized
FR4	The part should be optimized for LPBF

The components will be prone to the load as specified below in Table 3.

Table 3: Specification of the loads

Loads	Locations (x, y, z) [mm from origin]	Magnitude [N]
Force 1 (Z direction)	(10.00, 113.00, -38.828)	1500
Force 2 (Y direction)	(10.00, 113.00, -38.828)	-1000
Force 3 (Z direction)	(-20.00, 37.00, -28.828)	-1000

2.1 Strategy

As discussed above, our main goal is to minimize the costs. To accomplish this, we will focus on part consolidation first. Part consolidation has a lot of benefits in reducing the number of parts, reducing the part interfaces and allowing for a better balance between geometry and load, which will result in a longer lifetime. Subsequently, we will do FEM analyses together with topology and generative design, which will reduce weight and material costs. During this design process our focus will be on minimizing the costs during production by looking at overhang, print orientation and post-processing steps.

3 Strategy for Topology Optimization

In this section, the approach to the problem will be discussed.

3.1 Shape optimization

We started off by applying the shape optimization to the existing parts. For this simulation, we applied the given loads as described in Table 3 and the holes for the bolts were constrained in all directions. This led to the result as shown in Figure 2.

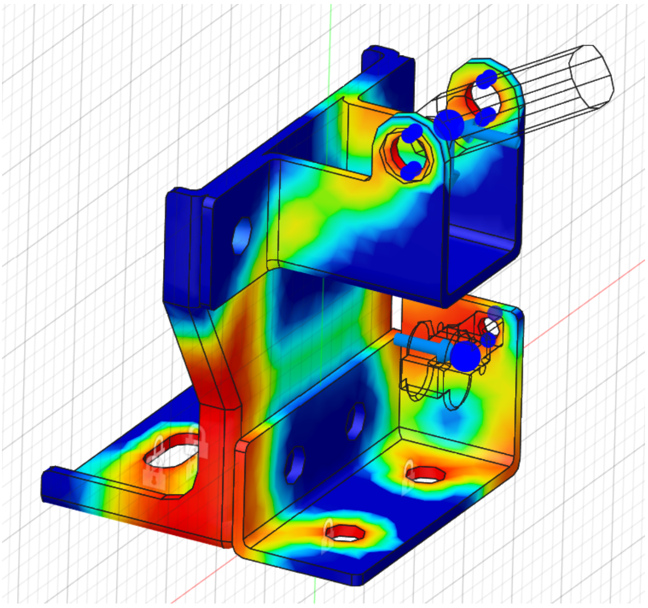
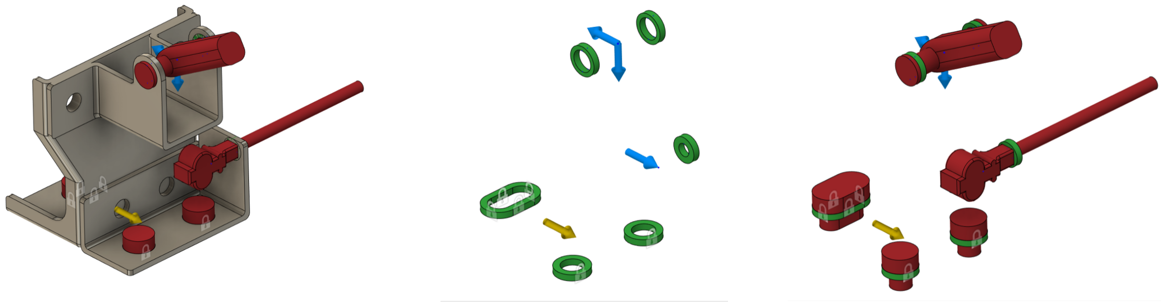


Figure 2: Shape optimization of existing assembly

Figure 2 clearly shows the areas where material could be removed. It will remove the material with the lowest stress. This way of working limits itself to removing material from the original shape. Since it can be seen that a more optimized shape should be possible by allowing material that is not within these limits we proceeded to our next step. In this step, we will perform a generative design study.

3.2 Generative design

We started off our generative design study by defining our geometric constraints. The bolts, hinge and sensor were selected in the original geometry as obstacles, as can be seen in red in Figure 3.
After that, the preserved geometry was created. Since we did not want the generative design study to limit itself to the earlier geometry, we created small rings around the old holes and deleted the rest of the geometry. The remaining rings were defined as geometry to be preserved, and the load case was applied. The applied loads and constraints are also visible in Figure 3, which are the same as discussed in the introduction.



(a) Original geometry (b) Preserved geometry with loads (c) Obstacle geometry

Figure 3: Generative design conditions

3.3 Results

As we proceeded, we had to change some parameters and run the model again. This report will not describe all these iterations of the model, but will only describe the important ones. The first iteration without any big errors (called Geometry-I1) can be seen in Figure 4. This iteration did not leave enough clearance around the holes for the bolts to fit in, all obstacle geometry was extended in the length direction and space was given for the screw head to fit in. This resulted in a geometry that intuitively looks right and has space for all the requirements (Geometry-I2). We have optimized this geometry further after the material selection.

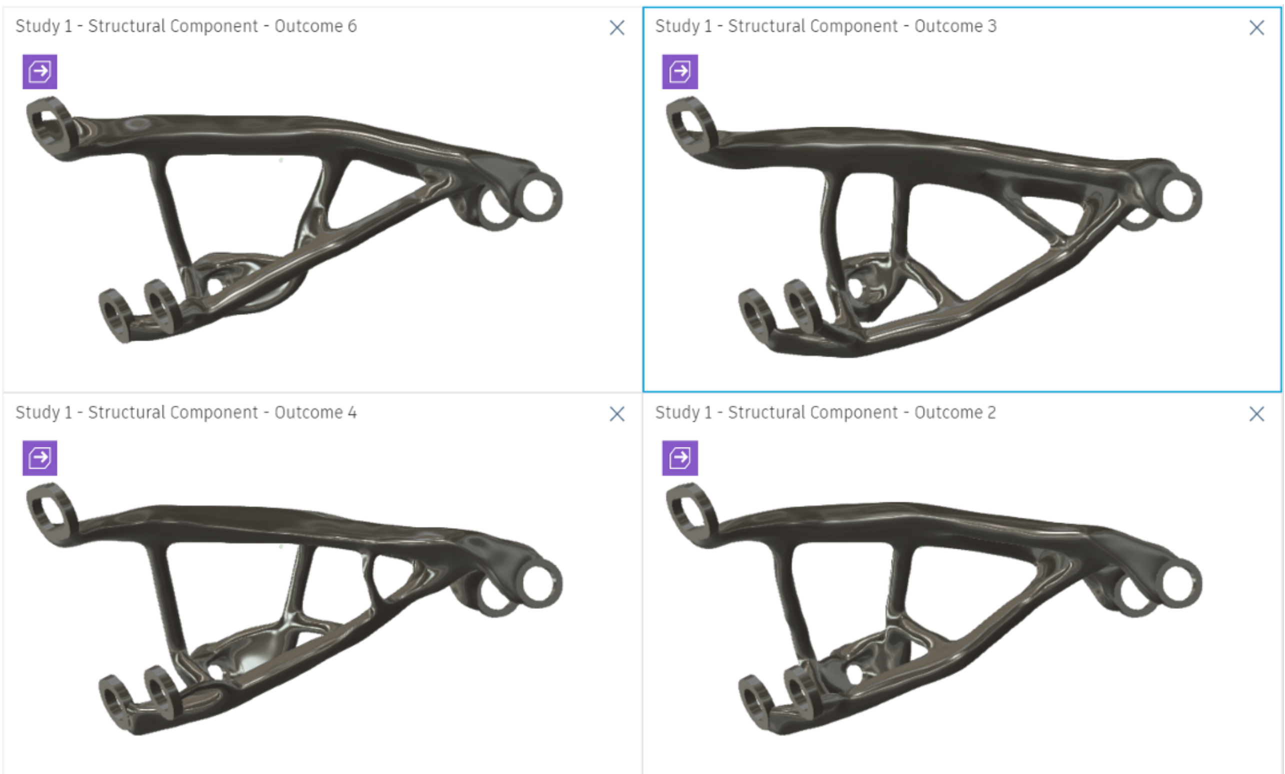


Figure 4: First results

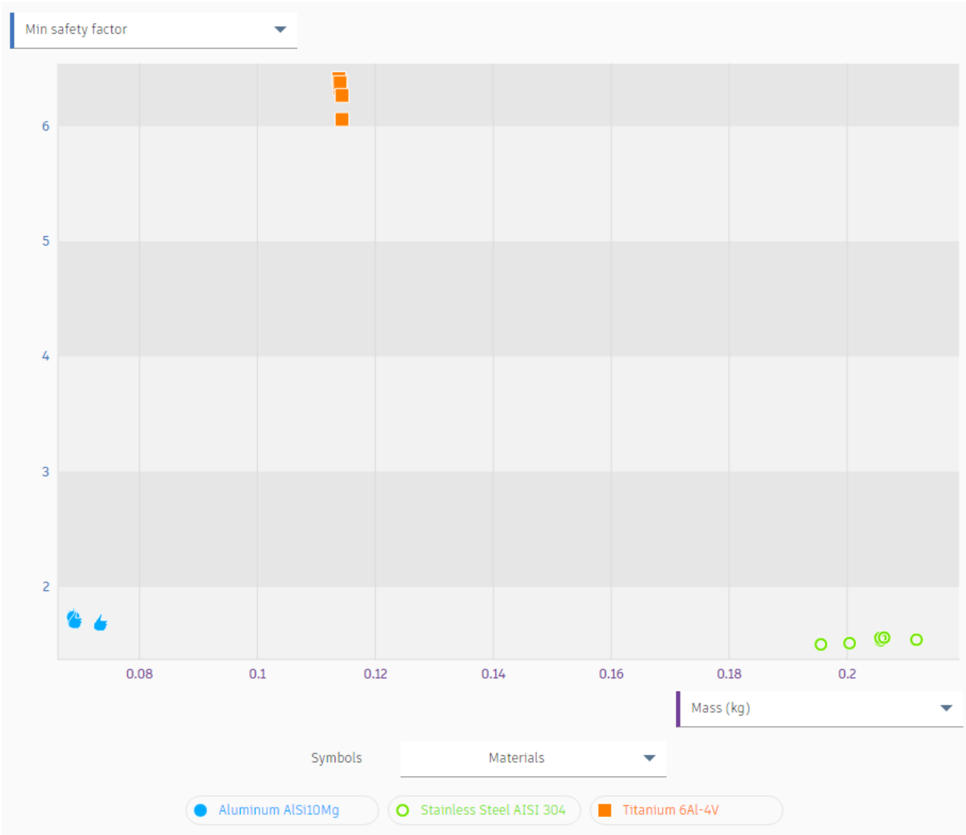


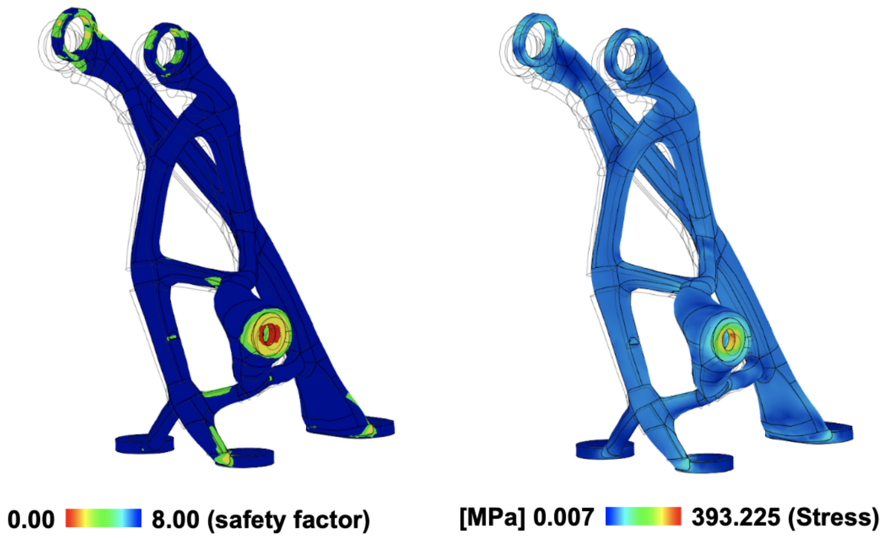
Figure 5: Three possible materials compared

3.3.1 Materials

Since our material selection was still open at this stage of the project, we ran the first study with Titanium 6AL-4V, Aluminum AlSi10Mg and Stainless Steel AlSI 304, the three common additive materials in the Fusion 360 library. Figure 5 shows the minimal safety factor (stress divided by tensile strength) against the mass of the outcomes of the first study with all three materials. It can be seen that the aluminum outcomes are the lightest, the titanium outcomes are the strongest, and the stainless steel outcomes are the worst in both aspects. Since both the aluminum and the titanium outcomes are above the safety factor limit, but the aluminum is lighter and probably cheaper, the aluminum outcomes are better for our use case in this scenario. Since the titanium outcomes are so high above the safety factor limit, we ran more simulations with only titanium while trying to remove more material to get a lighter model. This succeeded somewhat, but we never got close to the weight of the aluminum outcomes. For this reason, aluminum AlSi10MG will be the material for the rest of this project.

3.3.2 Static Load Simulation

Although generative design tries to create a geometry that can withstand the given load case, it is important to always run a static loads simulation to verify this. The results of the static load simulation of geometry-I2 can be seen in Figure 6. In this figure, it can be seen that the lower sensor mount hole experiences a von Misses stress which is about 0.7 of the safety factor. This means that the combined stress in this area is higher than the yield strength of the material, resulting in plastic deformation. To prevent this plastic deformation, the starting preserved geometry of the sensor mount ring was enlarged



(a) Safety factor (b) Stress

Figure 6: FEM analysis

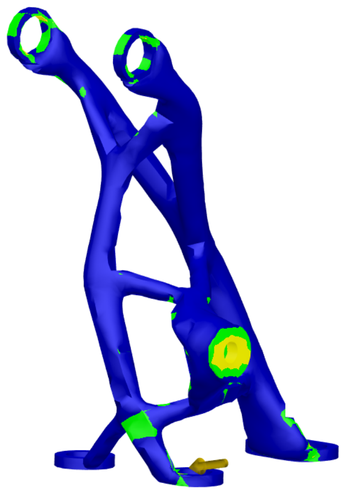


Figure 7: Adapted design

by 50 percent. After the study was run again, the new geometry was also simulated with a static load test, which results in Figure 7. In this figure, it can be seen that the von Misses stress is now higher than the safety factor.

3.3.3 Conclusion

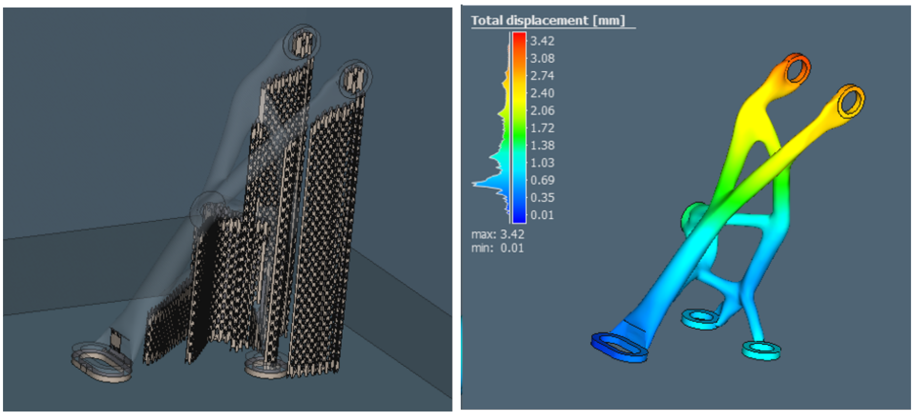
Although only one version of each iteration is described in this document, Fusion 360 creates many possibilities for each iteration. Of the last iteration (Geometry-I3), we selected the 4 best versions to study in Simulink, which look intuitively right. All these versions are quite comparable, as can be seen in Table 4.

	Version 1	**Version 2**	**Version 3**	**Version 4**
Volume (mm^3)	26.597,9	26.593,1	26.629,6	26.586,2
Mass (kg)	0,071	0,071	0,071	0,071
Max von Mises Stress (MPa)	98,5	95,8	96,2	97,3
Safety factor	2,43	2,50	2,50	2,47
Max displacement (mm)	0,269	0,255	0,246	0,255

Table 4: Versions outcome comparison

4 Strategy for AM Simulation

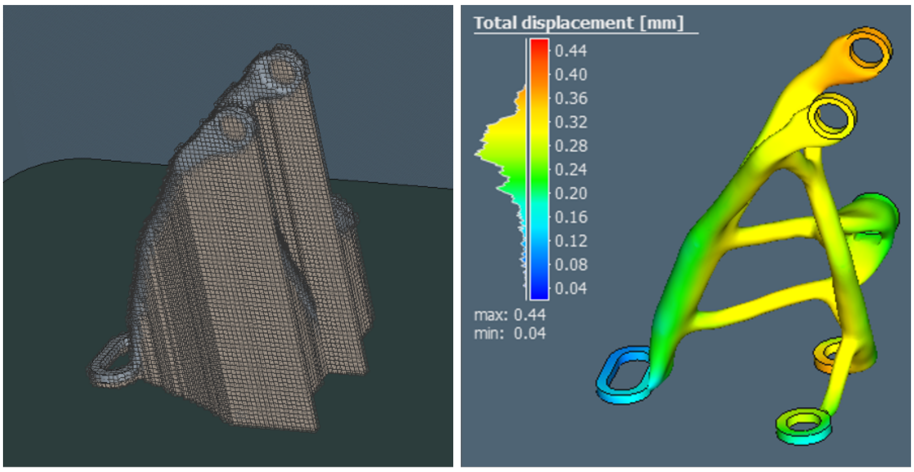
Our strategy for the AM simulation is to try to find the orientation with the least amount of support structure required. Besides that, we will take a look at displacements after support removal and optimize the support accordingly. During this process, the amount of (waste) material used for the support was weighted less than the gain that we could accomplish by minimizing the displacement and therefore post-processing steps. We started off in SimuFact by trying different orientations as shown in Figure 8.



(a) Support (b) Displacement

Figure 8: SimuFact first run

In this support structure we use 12.4 gram of Aluminium or 5757 mm^3. From Figure 8 it can be seen that the displacement after support removal and printing is quite large, up to 3.42 mm. Therefore the simulations was ran again but now with the settings for an optimized support structure. This led to the result as shown in Figure 9.



(a) Support (b) Displacement

Figure 9: SimuFact optimized run

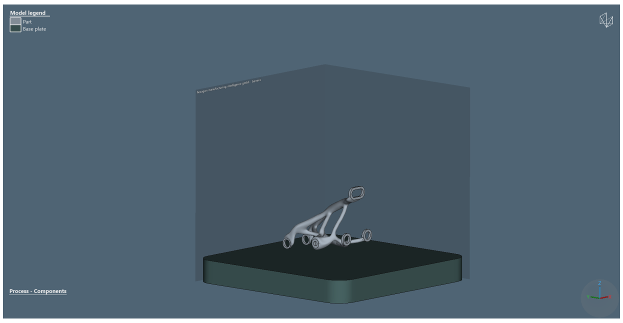
From the figure it can already be found that the support structure is a lot larger and complex. In this structure 84.7 gram of aluminium is used with a volume of 31380 mm^3. We played around a bit with those values and several options were analysed as will be analysed more in depth in the next chapter.

5 LPBF Analysis

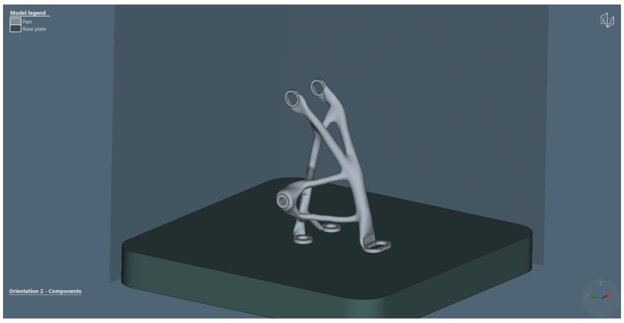
This chapter looks at part orientation, support structures, and thermal simulation within the LPBF process. Different build orientations were simulated using Simufact Additive to evaluate the influence of orientation on deformation, support material needed, and overall print time. The default and optimized support conditions were compared in an attempt to look at their influence on part accuracy and manufacturability. Next, the Orientation Assistant feature was used to provide auto-suggestions of better build directions for various design variants. Then, the final geometry was optimized using further simulations such as support removal, cutting, and heat treatment. All these operations were used to predict and reduce deformation so that the final part meets manufacturing tolerance.

5.1 Orientation

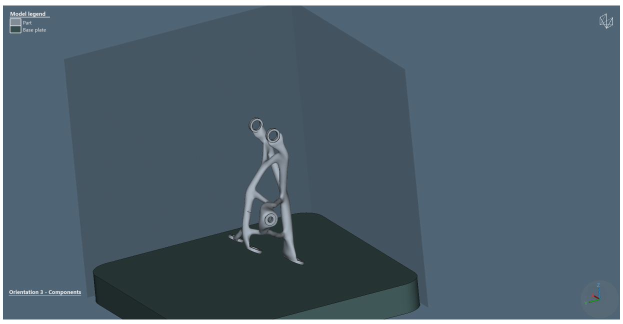
Initially, four manually selected build orientations were tested in Simufact. These orientations were chosen based on general design guidelines for additive manufacturing, such as maintaining key surfaces close to the build plate and minimizing overhangs. The goal was to find a balance between low deformation and reduced support requirements. Simulations were performed without any optimization settings to evaluate how orientation alone affects part quality, material usage, and printing time.



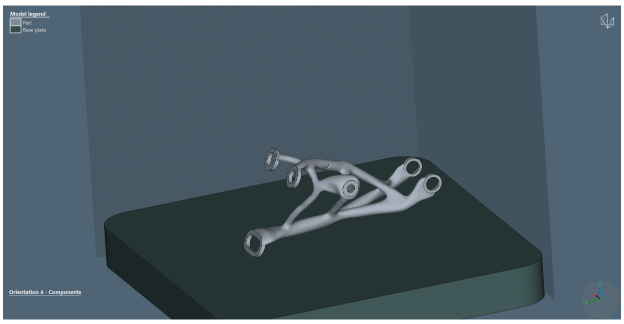
(a) Orientation 1



(b) Orientation 2



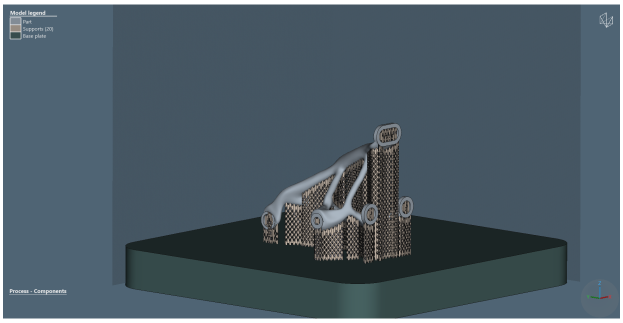
(c) Orientation 3



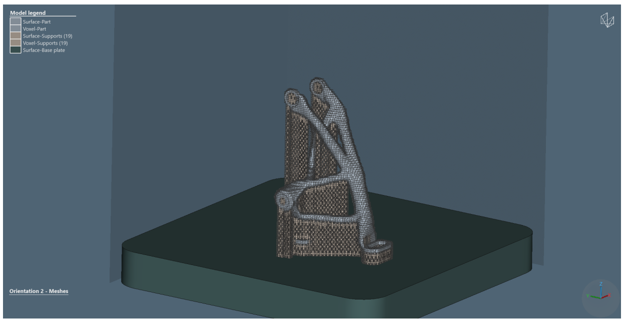
(d) Orientation 4

Figure 10: Different simulated print orientations without support structures.

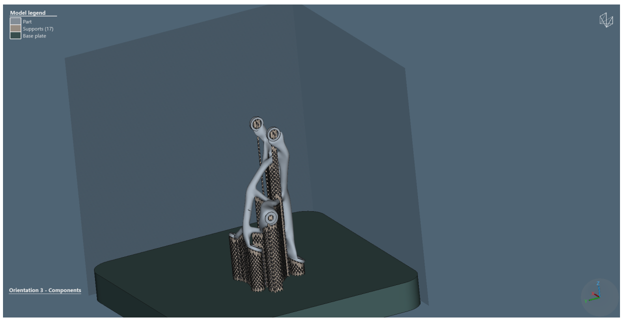
When applying the default support generation in Simufact, clear differences in the amount of support material can be observed across the orientations. This has a significant impact on overall print time. Without any optimization, Orientation 1 has a print time of 10h39 , Orientation 2 12h12, Orientation 3 14h13, and Orientation 4 completes in 8h59.



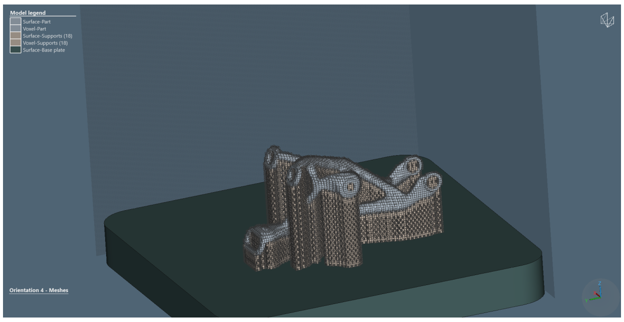
(a) Orientation 1



(b) Orientation 2



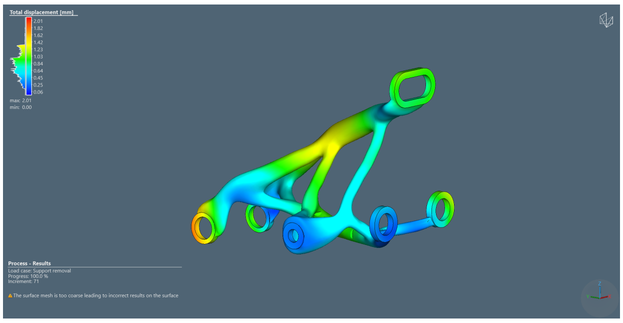
(c) Orientation 3



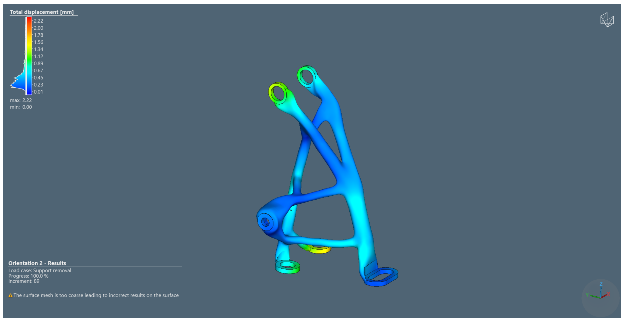
(d) Orientation 4

Figure 11: Generated support structures for each orientation using default settings.

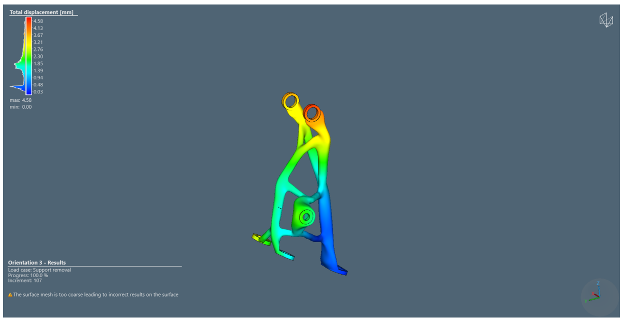
The deformation results highlight the need for support structure optimization. Using only the default settings, all orientations show excessive deformation, with displacement reaching over 4 millimeters. While the deformation is too high for a successful print in all cases, differences between orientations are already visible. Orientations positioned closer to the build plate tend to deform less, which also aligns with shorter print times as shown in the previous support structure simulations. These observations indicate which orientations are more promising moving forward.



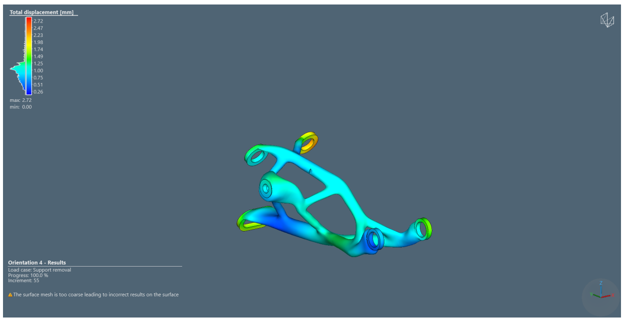
(a) Orientation 1



(b) Orientation 2



(c) Orientation 3

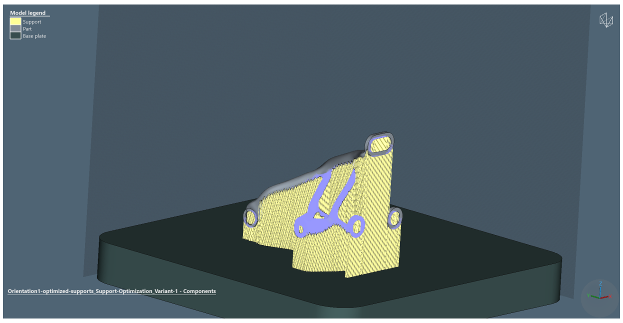


(d) Orientation 4

Figure 12: Displacement results for each orientation using default support settings.

Based on the earlier results, Orientation 1 and Orientation 4 were selected for further analysis. For both cases, optimized support structures were generated. These are shown in Figure 13. As can be seen, the amount of support material has increased significantly. This leads to higher material use and longer print times.

For Orientation 4, the print time increased to 11h38, using approximately 100 grams of support material compared to 25 grams in the unoptimized version. Orientation 1 even has an increased print time of 13h06. The deformation results for both cases are discussed in the next section.

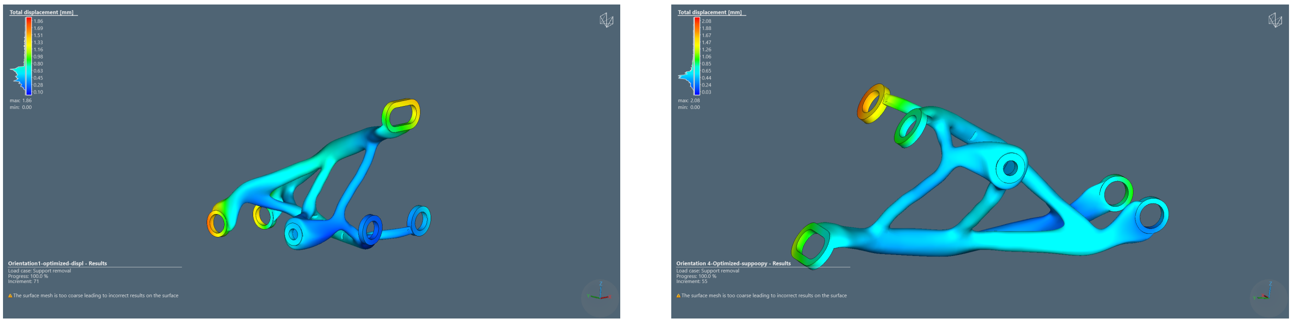


(a) Orientation 1 – Optimized Support

(b) Orientation 4 – Optimized Support

Figure 13: Optimized support structures for selected orientations.

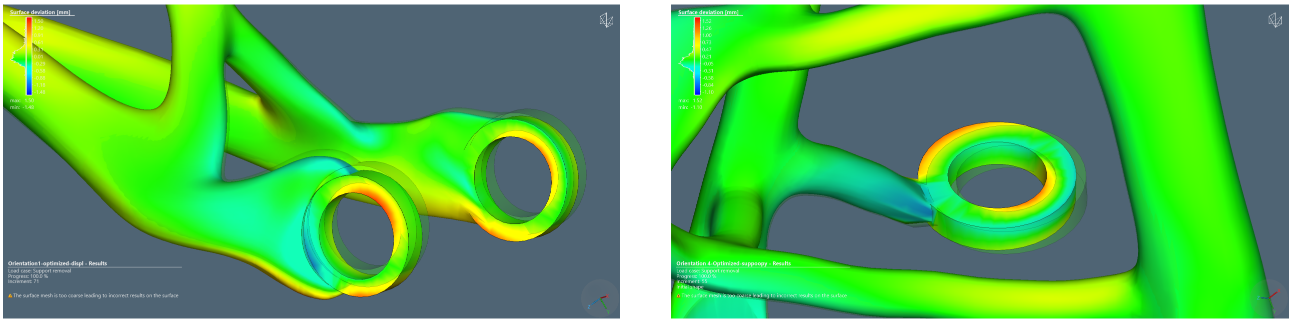
The deformation analysis after applying optimized support structures shows a clear improvement. However, displacement remains present. For Orientation 1, the total displacement is approximately 1.8 mm, while for Orientation 4 it reaches up to 2.0 mm after running a simulation to remove the supports. These results are shown in Figure 14.



(a) Orientation 1 – Optimized Support Displacement (b) Orientation 4 – Optimized Support Displacement

Figure 14: Displacement results with optimized support structures.

Further inspection shows that most of the displacement occurs near the hole and is mainly planar to it. A maximum deviation of 1.5 mm is observed in that region. Since these holes are quite important and need to be nicely aligned with each other, some kind of machining is unavoidable here. Therefore, we plan to keep the holes entirely closed from now on during the LPBF process and drill the holes afterwards, which will also reduce the impact of the distortion in this area. In the next design iteration in Fusion, the area around the hole will be thickened to help maintain strength. Considering both the displacement in all areas and the print time, orientation 4 is the best option.

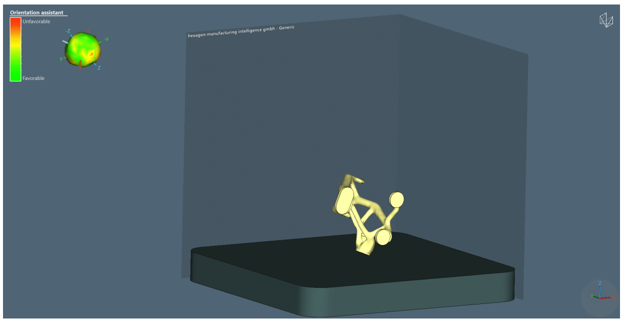


(a) Orientation 1 – Deformation Around Hole (b) Orientation 4 – Deformation Around Hole

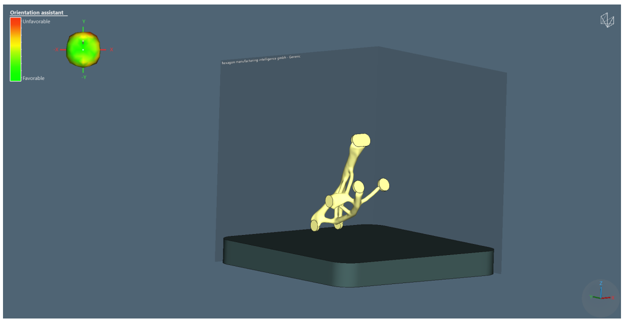
Figure 15: Detailed deformation around the hole area.

To explore possible improvements beyond the manually chosen orientations, the Orientation Assistant tool in Simufact was used. This tool automatically suggests build orientations by optimizing for support area, support volume, build costs, and build risk. The assistant was applied to four iterations of the generatively designed part. In these versions, the holes were filled to prepare for post-print drilling, as discussed earlier.

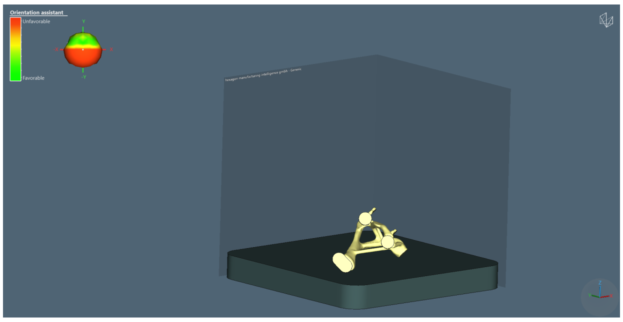
The resulting orientations for each iteration are shown in Figure 16, and their corresponding evaluation data are presented in Figure 17. Based on this data, the third iteration showed the most favourable results, with the lowest overall build cost, support surface area, and reasonable build risk. Therefore, this version will be used for the next steps in the development process.



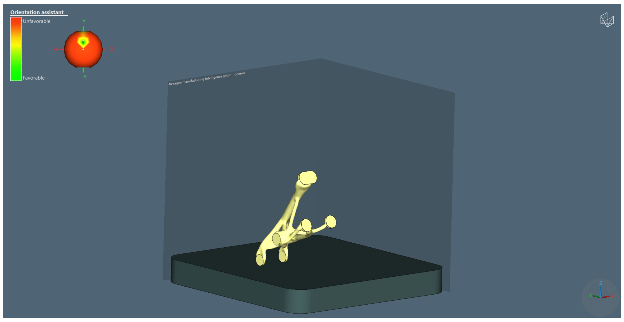
(a) Iteration 1



(b) Iteration 2

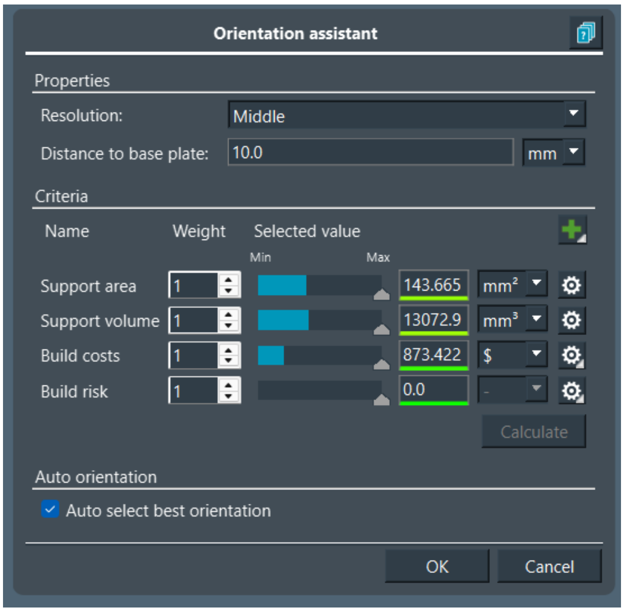


(c) Iteration 3

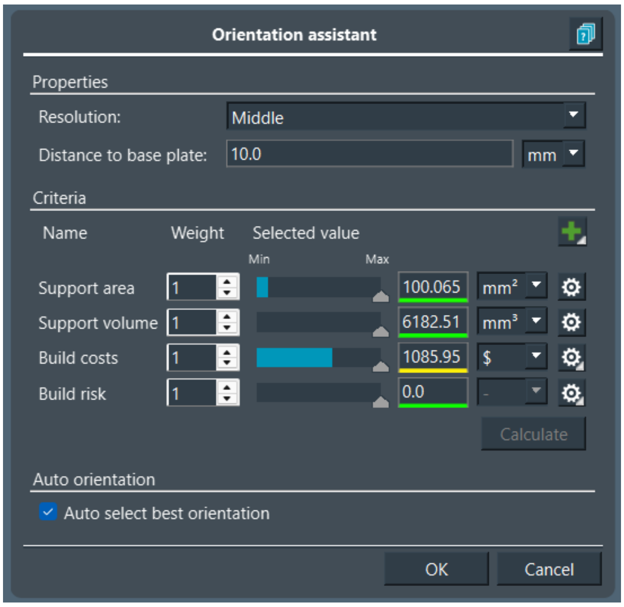


(d) Iteration 4

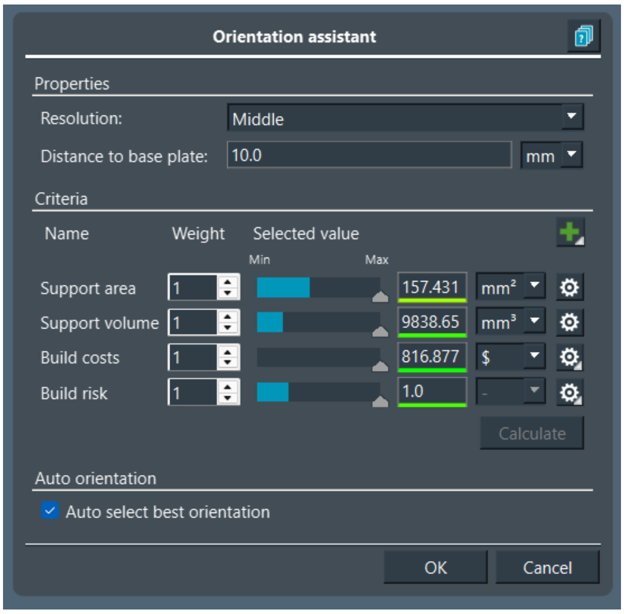
Figure 16: Suggested orientations by the Simufact Orientation Assistant for four generative design iterations.



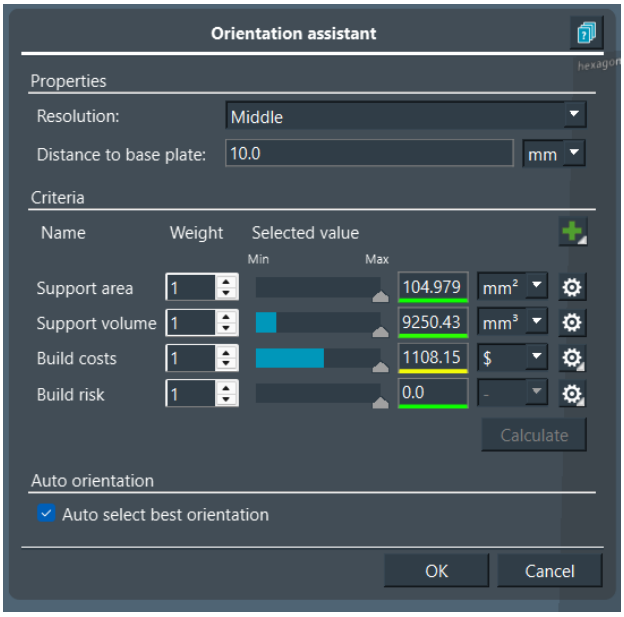
(a) Iteration 1



(b) Iteration 2



(c) Iteration 3



(d) Iteration 4

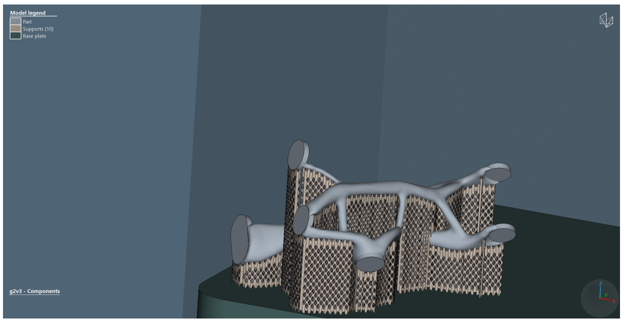
Figure 17: Orientation performance data from the Simufact Orientation Assistant. Iteration 3 shows the lowest build cost and favourable support metrics.

5.2 Final Iteration and Optimization

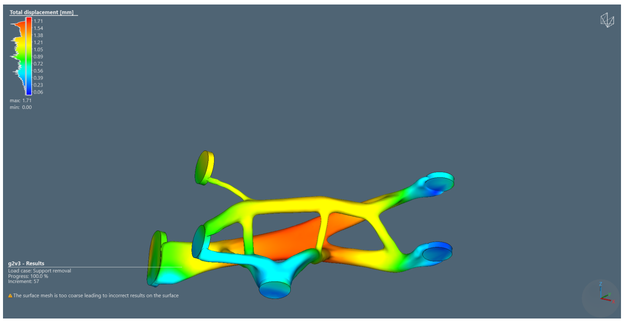
From this point forward, only the third generative design iteration, as shown in Figure 16 and Figure 17, was used. This iteration had the lowest estimated build costs according to the Orientation Assistant and required fewer support structures on complex surfaces. Reducing supported faces can contribute to easier and cheaper post-processing.

The model was first simulated using automatic, unoptimized supports. This initial setup is shown in Figure 18a. The resulting deformation after removing these supports is presented in Figure 18b.

A maximum displacement of up to 1.7 mm was identified, indicating the need for further support optimization to improve part accuracy.



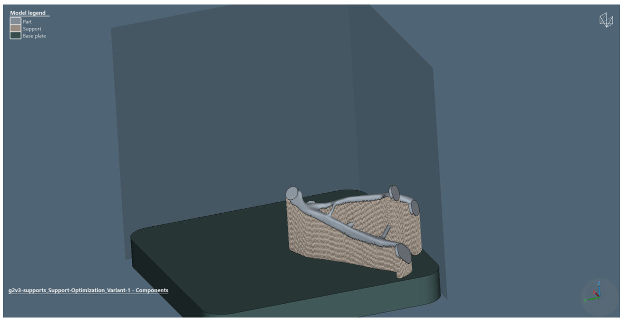
(a) Initial support structures generated automatically for the final geometry.



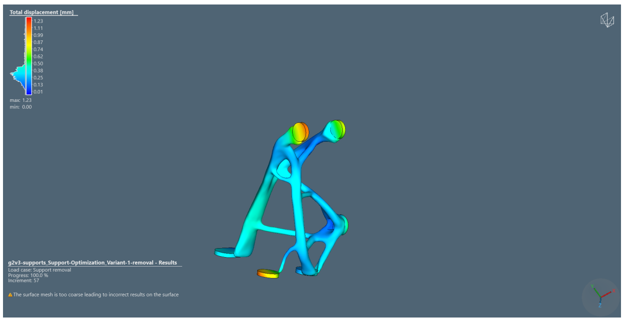
(b) Displacement results after removal of unoptimized support structures, showing a displacement up to 1.7 mm.

Figure 18: Initial support generation and deformation results before optimization.

To reduce the deformation, optimized supports were generated. Figure 19a shows the new support configuration. With this support, the deformation was reduced significantly, as shown in Figure 19b. A maximum displacement of 1.23 mm was observed.



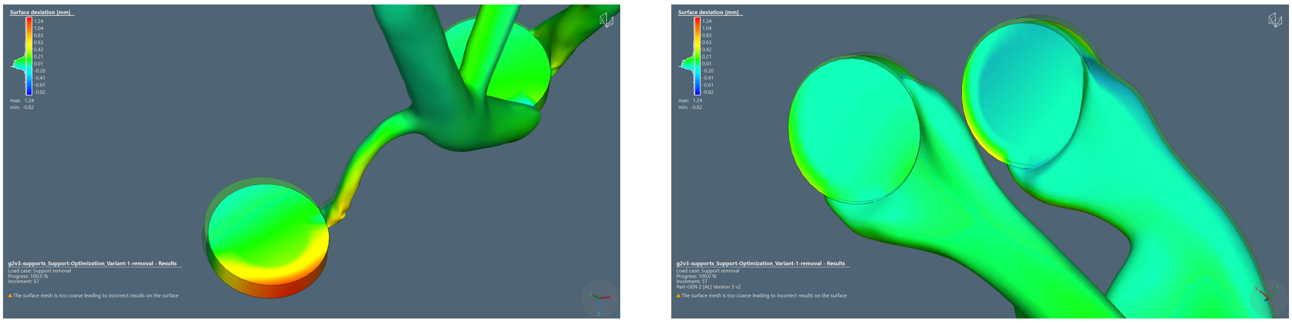
(a) Final model with optimized support structures.



(b) Displacement after removal of optimized supports. Maximum displacement is reduced to 1.23 mm.

Figure 19: Optimized support structures and resulting displacement.

To better understand where deformation occurs, surface comparison maps were generated. Figure 20a and Figure 20b show the distribution of deviations. The surface deviation appears near one of the holes, reaching just above 1.2 mm. Since these holes are designed to be redrilled and have been adapted to the expected deviations, this is not considered problematic.



(a) Surface deviation analysis after optimized support removal. Highest deviation is located near one of the screw holes.

(b) Additional surface deviation map confirming the critical area near the screw hole.

Figure 20: Surface deviation analysis after optimized support removal.

To achieve higher accuracy, a more realistic cutting simulation was performed. The previous simulations used the “Immediate Release” approach, which shortens computation time but lacks accuracy. The cutting simulation reflects the actual process of support removal from the base plate. As shown in Figure 21, this method predicted a displacement of 1.18 mm after support removal, again mostly planar around the hole region, deviation that was accounted for in the updated design.

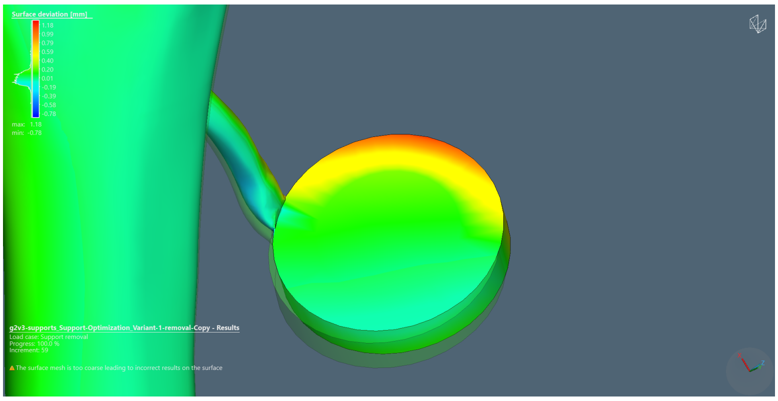


Figure 21: Displacement results from cutting simulation stage, showing a more accurate surface deviation of 1.18 mm.

Figure 22 shows additional local deformation in the lever region. Compared to earlier simulations, this area now shows less displacement after the cutting simulation.

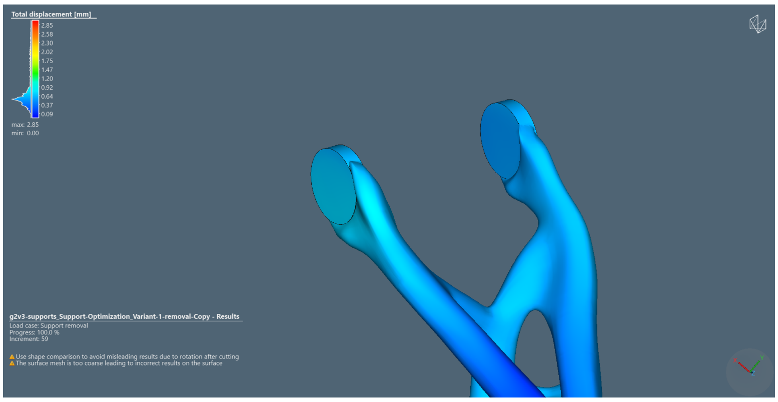


Figure 22: Displacement in the lever side after cutting simulation. Deformation has been reduced compared to previous steps.

To relieve internal stresses induced during printing, a heat treatment simulation was performed. Heat treatment is essential to reduce residual stresses caused by the high thermal gradients in LPBF. As seen in Figure 23, the resulting part experiences significant deformation, with displacements reaching almost 5 mm in critical regions, which is outside of the acceptable tolerances.

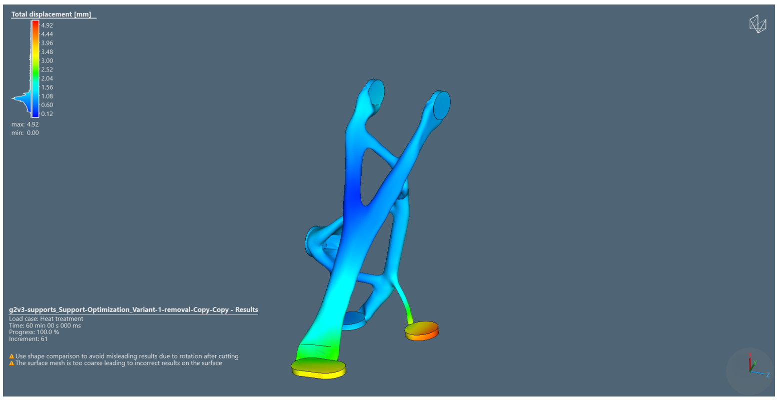


Figure 23: Displacement after stress relief heat treatment. Deformation reaches nearly 5 mm, exceeding specifications.

A comparison simulation was conducted for the first iteration of the generative design. The same steps were applied: optimized support generation, cutting simulation, support removal, and heat treatment. Figure 24 shows that this version still reaches a maximum displacement of 3.0 mm, which remains outside acceptable limits.

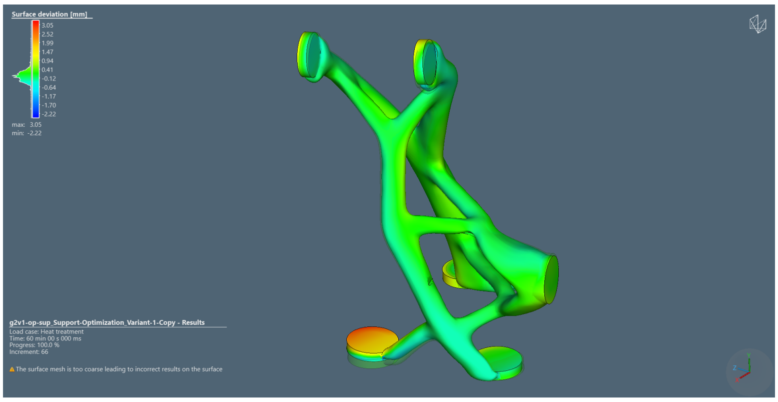


Figure 24: Final displacement result for the first generative iteration. Surface deviation up to 3.0 mm.

To reduce this distortion, a distortion compensation step was run on the third design iteration, due to its lower print cost. After this step, shown in Figure 25, the maximum surface deviation was below 0.5 mm.

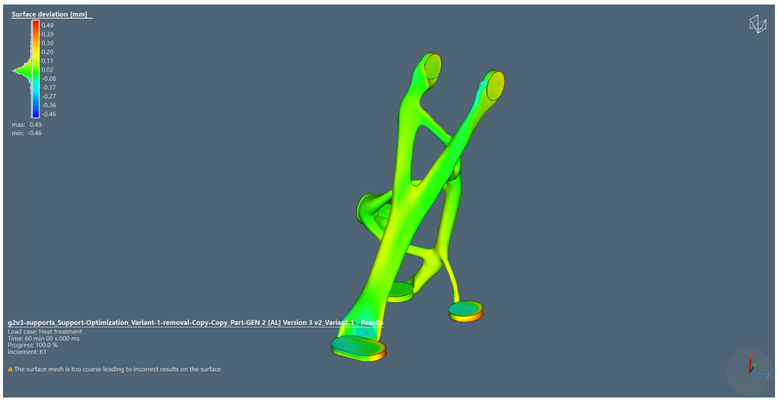


Figure 25: Displacement after distortion optimization, bringing deviation below 0.5 mm.

For final verification, a transient heat treatment simulation was run. This detailed analysis takes into account the temperature-time history and material model to simulate stress relief. Although it requires more computation time, it gives a more accurate result. The model was treated at 400 °C for 3 hours as can be seen in Figure 26.

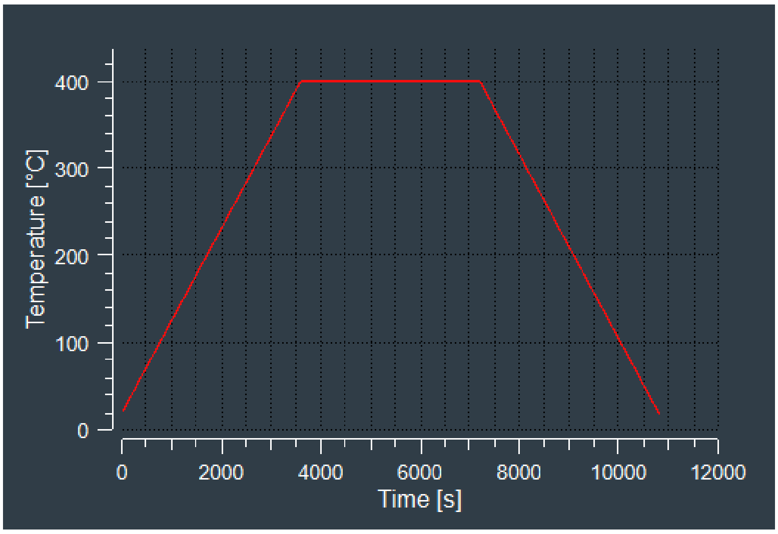


Figure 26: Transient heat treatment simulation at 400 °C for 3 hours.

After distortion compensation and transient heat treatment, the final predicted surface deviation is reduced to only 0.11 mm, as shown in Figure 27. The part is now within specifications and ready for manufacturing.

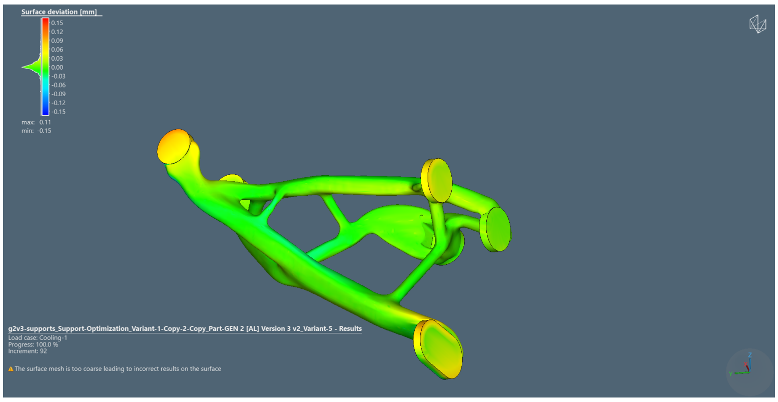
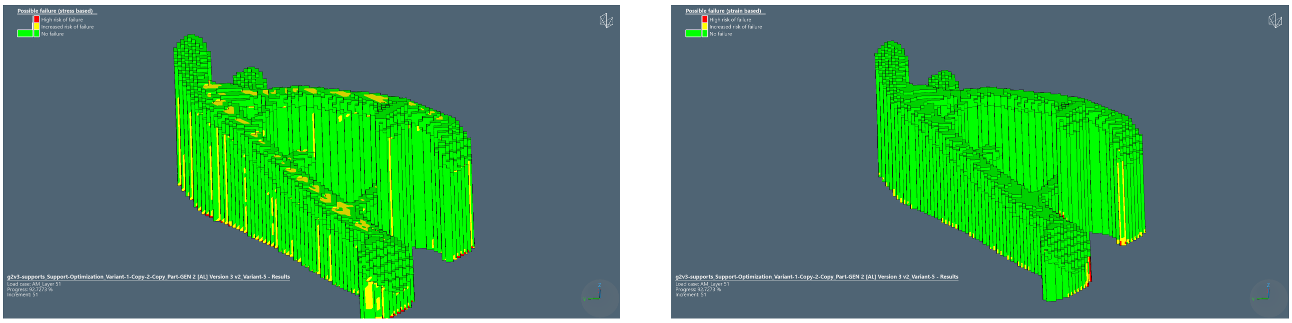


Figure 27: Final deviation after all optimizations. Maximum deviation is reduced to 0.11 mm.

Finally, failure criteria were also checked as part of the final validation. Figure 28a and Figure 28b show stress and strain distributions across the part after printing. This shows little to no areas with a high risk of failure.



(a) Simulated stress levels.

(b) Simulated strain results.

Figure 28: Final simulation of stress and strain distributions after printing.

5.3 Post-processing

As discussed before, after the LPBF process we will do a stress relieve. For this, we will apply the annealing heat treatment at 240° to 300° for about 1-2 hours. In SimuFact we simulated this at a slightly different time and temperature due to limitations in the software, but these are the real values suggested [1]. Since additional heat treatments are uncommon for AlSi10Mg and heat treatments like aging and HIP at high temperatures can even reduce the yield strength of AlSi10Mg, this will be the only heat treatment applied [1].

5.4 Final steps

Next, the support structures will be removed. For this, wire EDM and some small manual tooling will be used. Subsequently, the holes that were not incorporated in the AM design (to compensate for misalignments and displacement after support removal) need to be drilled. For this, the part needs to be machined.

6 Detailed Cost Calculation

Now that the manufacturing process is known, we took a look at the costs. For the cost calculation, the following assumptions as given in the assignment were used:

- €30 per surface for support removal on non-critical surfaces
- €60 per surface for support removal on critical surfaces
- €100 per surface for reworking critical surfaces with deformations/misalignments exceeding 0.1 mm

6.1 Key cost drivers in LPBF simulation

Cost estimation in LPBF processes takes multiple things into account. While Simufact's cost analysis module requires three inputs: machine hourly rate, fixed operational costs, and material powder cost, there are additional cost components that impact total production cost [2].

The machine hourly rate calculation includes printer depreciation, maintenance, and facility overhead. For LPBF systems operating at 70–90% utilization over 5 years, hourly rates typically range from €70 to €150. This aligns with cost calculations for a €700,000 multi-laser PBF machine depreciated over 10,000 operational hours:

$$C_{hour} = \frac{C_{capital} + C_{maintenance}}{T_{operational}} = \frac{700,000 + 15,000/yr}{10,000\,\text{h}} = 77.5/\text{h} \tag{1}$$

Material costs for AlSi10Mg powder range from €51–70/kg for small quantities down to €24–35/kg for bulk orders above 1,000 kg [3]. For this study, a bulk rate of €35/kg is assumed.

Secondary Cost Factors Post-processing accounts for up to 40% of total LPBF costs, including things like:

- Stress relief heat treatment: €500–€2,000 per batch
- Support removal: €200–€300 per build plate
- Surface finishing: €200–€2,000 depending on tolerances and geometry

Labour remains a big contributor to these costs. Skilled workers are required for setup, post-processing, and quality control. Vaneker et al. [4] highlight support removal and surface reworking as primary labour drivers.

Machine Fixed Costs Fixed costs per build primarily stem from setup and calibration operations, such as scan path alignment and thermal system preparation. We estimate calibration for multi-laser systems to take approximately 68 minutes. The cost can be approximated as:

$$C_{fixed} = t_{setup} \times C_{labour} \tag{2}$$

Here, t_{setup} is setup time in hours, and C_{labour} is the hourly technician cost, typically €45–€150/h. €100 set-up cost is used for this study.

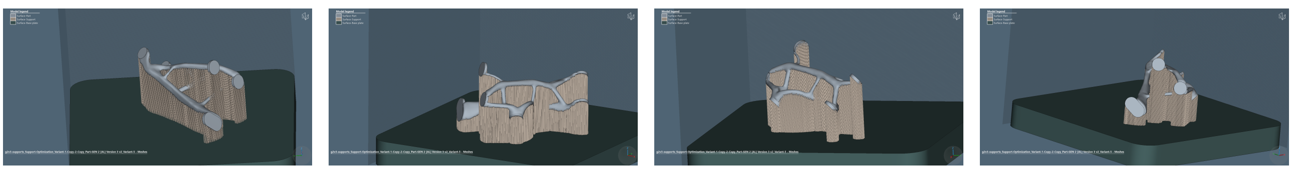
6.2 Print Job Specific Cost Estimation

The final part geometry has a print time of 12 hours and 43 minutes. Using the assumed machine hourly rate of €77.50:

$$C_{print} = 12\text{h}43 \times 77.50 = 985.80 \tag{3}$$

Powder material usage totals €6.65, based on the volume required and the €35/kg bulk price. Post-processing steps include redrilling, support removal, and thermal treatment:

- **Drilling the holes:** 6 critical surfaces need post-machining at €100 each: €600 total
- **Support removal:**
  - 8 non-critical supported faces at €30 each: €240
  - 6 critical supported faces at €60 each: €360



(a) View 1 (b) View 2 (c) View 3 (d) View 4

Figure 29: Different views of the final model with supports.

6.3 Additional Labour Considerations

The part also requires labour for:

Cutting from Build Plate dAfter printing, the part is removed from the base plate via wire EDM. This step is estimated at:

$$C_{\text{cutting}} = 80$$

Heat Treatment Handling Preparation and handling for stress relief requires loading, unloading, and monitoring. Labour cost for this is estimated at:

$$C_{\text{heatlabour}} = 100$$

6.4 Updated Total Cost Estimate

Summarizing all cost components:

- Fixed machine setup: €100
- Printing time (12h43 at €77.5/h): €985.54
- Powder material: €6.65
- Rework for drilling tolerances: €600
- Support removal: €240 + €360 = €600
- Cutting from base plate: €80
- Heat treatment handling: €100

Final estimated cost per print:

$$C_{\text{total, updated}} = 100 + 985.80 + 6.65 + 600 + 600 + 80 + 100 = \textbf{€2472.45}$$

This estimate represents the full production cost of the part, including equipment use, material, labour, and post-processing.

7 Conclusion

The geometry of the final design was checked against all the functional and technical requirements. From this, it could be concluded that it fulfils all set requirements. The final geometry, as can be seen in Figure 30 was designed with Generative Design in Fusion 360 with the load cases given at the start of the project. A static load test with FEM was applied to the geometry to validate its strength and increase material where necessary. Furthermore, the 4 lightest models were all reviewed for strange artifacts or errors in the simulation.
The resulting geometry was imported into SimuFact to simulate the build orientation, support structure, heat treatment and to estimate the cost price. In the end, we managed to create a design that weighs about 0.071 kg, has a maximum deformation of 0.11mm from the original and costs €2472.45.

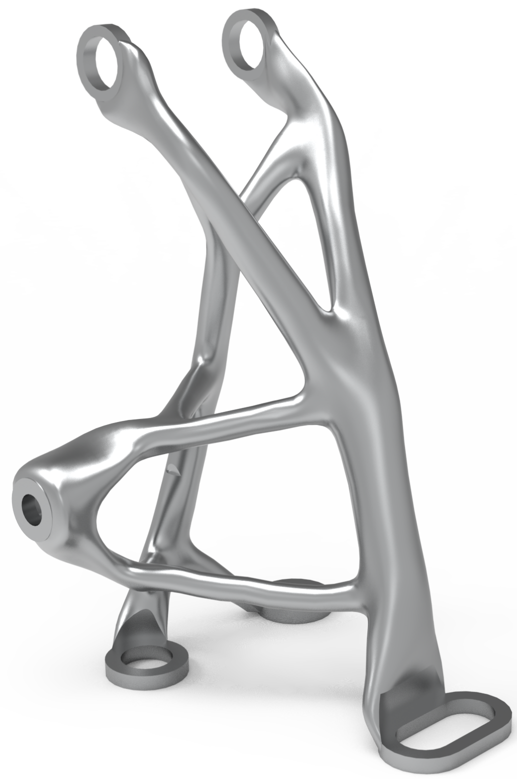


Figure 30: Final Design

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[1] C. H. Lim, H. Li, M. Krishnan, K. Chen, and J. Li, "Novel method of residual stress reduction for AlSi10Mg manufactured using selective laser melting without compromise of mechanical strength," *Virtual and Physical Prototyping*, vol. 18, no. 1, 1 2023.

[2] SIMTEQ Engineering, "Simufact additive cost estimation," *SIMTEQ Blog*, 2020. [Online]. Available: https://simteq.co.za/blog/sharpen-the-saw-simufact-additive-cost-estimation/

[3] MET3DP, "Alsi10mg powder for SLM/EBM 3d printing," 2024. [Online]. Available: https://met3dp.com/product/alsi10mg-powder/

[4] T. Vaneker, A. Bernard, G. Moroni, and I. Gibson, "Design for additive manufacturing: Framework and methodology," *CIRP Annals*, vol. 69, no. 2, pp. 578–599, 2020.